Report No. P67-82
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Sixth Quarterly Report

for

PARAMETRIC ANALYSIS OF MICROWAVE AND LASER SYSTEMS FOR COMMUNICATION AND TRACKING

(6 December 1966 – 6 March 1967)

Contract No. NAS 5-9637

Prepared by

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SUMMARY

PROGRAM STATUS

The National Aeronautics and Space Administration, in its space exploration program, has promoted space communications through hardware development and technical studies. August 6, 1965, the Goddard Space Flight Center, NASA, awarded the Hughes Aircraft Company a study contract for Parametric Analysis of Microwave and Laser Systems for Communications and Tracking, NAS 5-9637.

This study contract has three basic purposes: first, to collect the information and conclusions of previous studies and present them in a readily accessible form. Secondly, to formulate a "Reference Data for Advanced Space Communications and Tracking Systems" which will contain: (1) a methodology for solving space communication and tracking problems, (2) parametric studies of the parameters involved in the methodology and, (3) a state-of-the-art documentation of the parameter values. Finally, the third major purpose of the study is to evaluate the capability and amenability to modification of the available world-wide communication and tracking system to the increased performance requirements of future microwave and optical communications systems.

The Parametric Analysis of Microwave and Laser Systems for Communication and Tracking is to be conducted in two phases. Phase I had a six-month duration and Phase II has a thirty-three month duration. The study is presently at the twelve-month point of Phase II. The present program plan for the study is indicated in Figure 1. For calendar 1966 and 1968 this plan indicates periodic updating and enlargement of the first issue of "Reference Data for Advanced Space Communication and Tracking Systems." During 1967 the majority of the low level program effort will be devoted to determining optimum solutions of space communication configurations.

SIXTH QUARTER EFFORT

During the sixth quarter effort was expended on refinement of portions of the Methodology section and updating of the "Heat Radiator Systems" section.

	1966				1967				1968				
	1	2	3	4	1	2	3	4	1	2	3	4	
PHASE II PROGRAM PLAN SUBMITTED	Δ												
PHASE II GO-AHEAD		Δ											
UPDATING OF "REFERENCE DATA FOR ADVANCED SPACE COMMUNICATION AND TRACKING SYSTEMS"		■	■	■					■	■	■	■	
METHODOLOGY				*				*				*	
MISSION ANALYSIS		*		*						*		*	
COMMUNICATION THEORY			*							*			
TRANSMITTING POWER SOURCES		*							*		*		
DETECTORS			*							*			
MODULATORS		*							*		*		
ACQUISITION AND TRACKING		*	*							*	*		
RADIO FREQUENCY ANTENNAS			*								*		
OPTICS				*					*			*	
PRIME POWER				*									
RADIATION BACKGROUND AND ATMOSPHERIC PROPAGATION		*								*			
GROUND RECEIVING SITES				*								*	
HEAT RADIATORS					*				*				
SYSTEMS IMPLEMENTATION			*						*		*	*	
COMMUNICATION SYSTEM PROBLEM SOLUTIONS					■	■	■	■	■	■	■	■	
QUARTERLY REPORTS				Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	
QUARTERLY REVIEW MEETINGS				Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ
FINAL REPORT													Δ

* TECHNICAL SECTION UPDATED

Figure 1. Program plan for Parametric Analysis of Microwave and Laser Systems for Communications and Tracking.

The Methodology, as given in the 6 December 1966 issue, provided a means of determining an optimum centerline design for a communications system. Optimization to date has been made on the basis of minimized cost.* However optimization on the basis of weight is easily implemented in the computer programmed optimization procedure by setting certain parameters to zero. The computer program accuracy is, of course, critically dependent upon the input data it receives. Much of this data is empirical. For example, the relationship between an antenna weight and its diameter is given the computer by the relationship

$$W_{d_T} = K_{d_T} (d_T)^{n_T} + W_{K_T}$$

*Since a dominant cost of space hardware is putting the payload in space, optimizing on the basis of cost, in essence, minimizes payload weight.

where

W_{d_T} is the antenna weight

d_T is the antenna diameter

n_T is a constant but not necessarily an integer

W_{K_T} is a fixed weight

The constants of this equation are determined empirically and programmed into the computer. During the past quarter better empirical data has been gathered for parameter values such as the antenna weight noted above. Perhaps more significant is the successful operation of three computer programs with the fractional exponents, e.g., $n_T = 2.3$. These programs are: (1) the optical direct, thermal noise limited, detection (TOP), (2) optical heterodyne detection (HOP), and (3) the radio receiver program (ROP). The Fortran IV computer printouts of these programs are given in this report in Appendices A2.5, A2.6, and A2.7 of Section 2.0,. Methodology. Additional updated material is given as Methodology appendices in Appendices A2.1, Nomenclature; A2.2, Input Data Program; A2.3, Output Data Program.

The TOP, HOP, and ROP optimization programs have been used to calculate optimum system parameters for a Jupiter communication link. This was done for a carrier wavelength of 10.6 microns and a radio frequency of 2.3 GHz. While the data from these computer calculations must still be regarded as preliminary since sensitivity of the output data has not been correlated with input data and since the constants of the computer program input data have not yet been fully reviewed in all the technology areas, the data does provide very interesting comparisons and shows general trends.

The TOP, HOP, and ROP data is given in Figure 2, 3, and 4 and in Table 1. Figure 2 is a total cost comparison of the three systems made on the basis of an optimized minimum cost system. Booster cost and ground receiving system costs were considered in the optimization but only the spaceborne costs are shown in Figure 2. Figure 3 is a comparison of the spaceborne weights of these three systems which were selected on the basis of minimum cost. Figure 4 gives the variable parameter values for the cost optimized systems. Figures 2, 3, and 4 are all plotted as a function of bit rate and assume a 14 db receiver signal to noise ratio.

Table 1 contains a tabulation of the weights of the three systems. The total weight noted in Table 1 corresponds to the values given in Figure 3.

The second major area of emphasis during the past quarter has been the updating and revising of Section 14.0, Heat Radiator Systems. The material of this section has been revised to incorporate more data into the graphics and now includes weight and cost burden relationships. These are being used in the Methodology to determine optimum communications systems configuration based upon minimum cost or minimum weight systems.

Cost and weight burden relationships for technology areas other than Heat Radiator Systems have been examined during the last quarter. These will be incorporated in future reports with the complete updating of the corresponding technology section.

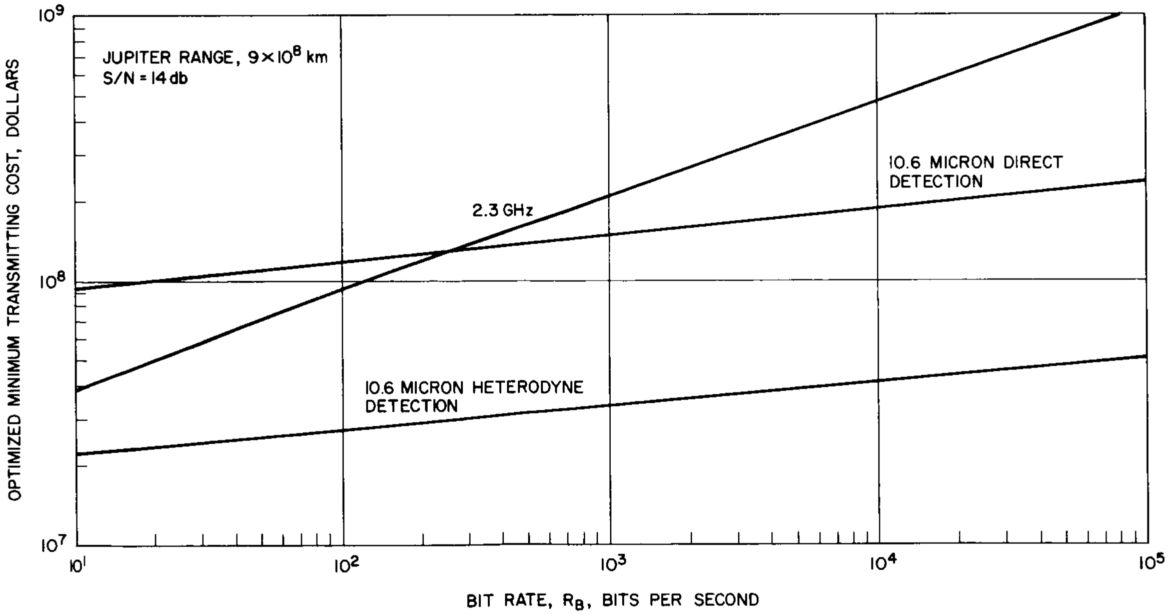


Figure 2. Spaceborne transmitting cost versus bit rate for an optimized minimum cost communication system at Jupiter range.

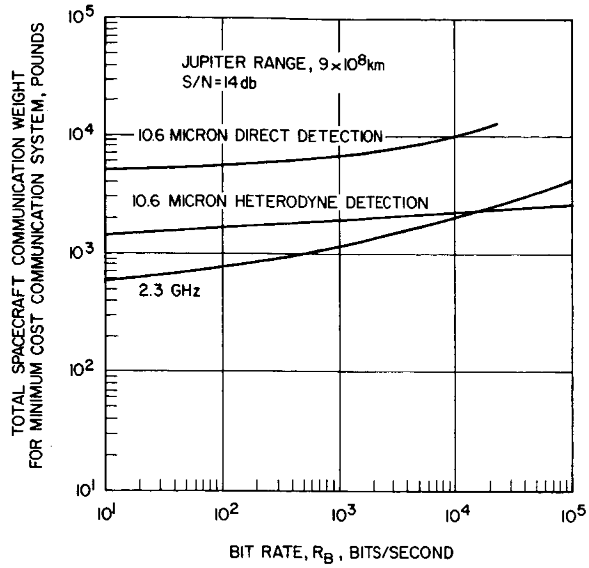
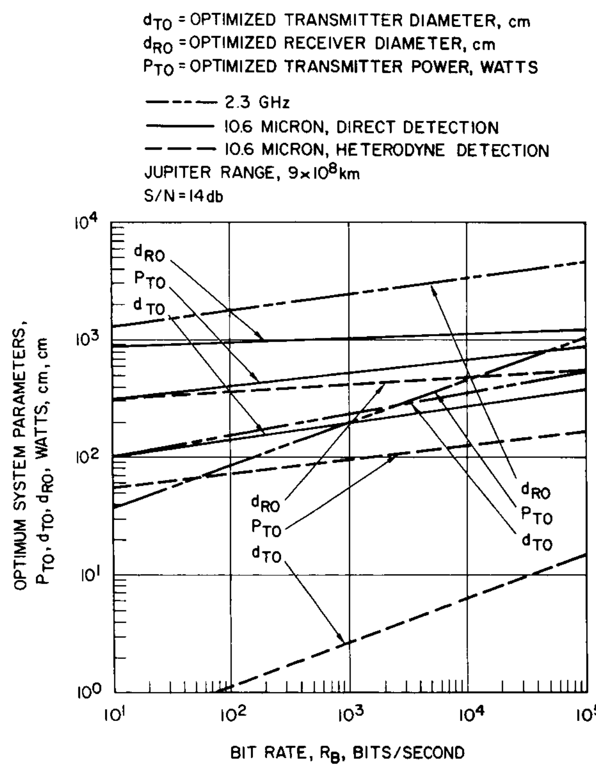


Figure 3. Total spaceborne weight of an optimized minimum cost communication system at Jupiter range.

Figure 4. System parameters versus bit rate for optimized minimum cost communication system at Jupiter range.



Bit Rate, R_B, bits/sec	Optimized Values (See Figure 3)			Telescope Weight, W_{dT}, lb	Transmitter Weight, W_T, lb	Power Supply Weight, W_{ST}, lb	Heat Exchanger Weight, W_H, lb	Acq. and Track System Weight, W_{QT}, lb	Modulator Weight, W_M, lb	Total Spacecraft Communication System, Weight, W_A, lb
	Transmitter Diameter, d_{TO}, cm	Receiver Diameter, d_{RO}, cm	Transmitted Power, P_{TO}, watts							
1.04×10^7	1263	8618	5608	689	566	17,711	416	527	0	19,908
1.55×10^6	893	6667	2804	344	285	9,087	208	268	0	10,193
1.26×10^5	565	4748	1122	138	117	3,912	83	113	0	4,363
1.02×10^4	357	3382	449	55	50	1,842	33	51	0	2,032
1.53×10^3	252	2616	224	28	27	1,152	17	31	0	1,254
695	219	2351	168	21	22	980	13	25	0	1,060
229	178	2023	112	14	16	807	8	20	0	866
34	126	1565	56	7	11	635	4	15	0	672

a. 2.3 GHz system.

Table 1. Optimum system parameters, weight, and total space communications system weight — Jupiter mission.

Bit Rate, R_B, bits/sec	Optimized Values (See Figure 3)			Telescope Weight, W_{dT}, lb	Transmitter Weight, W_T, lb	Power Supply Weight, W_{ST}, lb	Heat Exchanger Weight, W_H, lb	Acq. and Track System Weight, W_{QT}, lb	Modulator Weight, W_M, lb	Total Spacecraft Communication System, Weight, W_A, lb
	Transmitter Diameter, d_{TO}, cm	Receiver Diameter, d_{RO}, cm	Transmitted Power, P_{TO}, watts							
14,000	285	1226	702	835	1428	5758	442	2258	20	10,742
3,290	238	1115	590	590	1205	4835	372	1713	20	8,734
562	188	1003	484	377	992	3977	305	1242	20	6,913
61.5	136	891	387	209	799	3218	244	869	20	5,359
3.62	85.8	784	303	99	631	2594	191	623	20	4,158

b. 10.6 micron direct detection system.

Table 1. (continued)

Bit Rate, R_B, bits/sec	Optimized Values (See Figure 3)			Telescope Weight W_{dT}, lb	Transmitter Weight, W_T, lb	Power Supply Weight, W_{ST}, lb	Heat Exchanger Weight, W_H, lb	Acq. and Track System Weight, W_{QT}, lb	Modulator Weight, W_M, lb	Total Spacecraft Communication System, Weight, W_A, lb
	Transmitter Diameter, d_{TO}, cm	Receiver Diameter, d_{RO}, cm	Transmitted Power, P_{TO}, watts							
6.72×10^8	285	1226	702	835	1428	5758	442	2258	20	10,742
3.26×10^8	238	1115	590	590	1205	4835	372	1713	20	8,734
1.35×10^8	188	1003	484	377	992	3977	305	1242	20	6,913
4.46×10^7	136	891	387	209	799	3218	244	869	20	5,359
1.08×10^7	85.8	784	303	99	631	2594	191	623	20	4,158
1.71×10^6	44.5	685	234	45	492	2110	147	504	20	3,318
1.47×10^6	17.7	588	173	28	372	1718	109	467	20	2,714
4.49×10^3	4.63	479	116	25	257	1357	73	460	20	2,193
11.	0.464	339	58.7	25	142	998	37	460	20	1,682

c. 10.6 micron heterodyne detection system.

Table 1. (continued)

Report No. P67-82

FIFTH ISSUE

REFERENCE DATA FOR ADVANCED SPACE COMMUNICATION AND TRACKING SYSTEMS

6 March 1967

Contract No. NAS 5-9637

Prepared by

Aerospace Group
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Culver City, California

for

Goddard Space Flight Center
Greenbelt, Maryland

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1.0 INTRODUCTION

1.1 PURPOSE

"Reference Data for Advanced Space Communications and Tracking Systems" is being produced for the Goddard Space Flight Center by the Hughes Aircraft Company under NASA Contract NAS 5-9637. The purpose of this contract is to perform a parametric study with the following goals:

1. Perform overall systems tradeoff studies in sufficient detail to identify those missions which will make the best use of laser/optical, microwave, or a combination of microwave and laser/optical communication and tracking systems.
2. Provide a plan for optimumly integrating such future microwave and/or laser/optical communication and tracking systems into present and future world-wide systems.
3. Provide overall systems design criteria or specifications for microwave and/or laser/optical communication and tracking systems.

The first issue of "Reference Data for Advanced Space Communication and Tracking" provided preliminary data for the achievement of these goals. This data was presented in 13 technical sections, in addition to the introductory material. These technical sections were designed to meet the contract goals listed above, as follows:

- The Methodology section provides a basis for determining the optimum communication and tracking system configuration, whether it be at microwave, millimeter waves, or optical frequencies. The Methodology section, in its detailed documentation of functional relationships, also establishes the parametric studies which must be performed in each technological area.
- Two sections of the Reference Data will dominate in establishing a means of integrating future space communication systems with existing and future ground facilities. These

are Mission Analysis and Ground Receiving Sites. Mission Analysis is concerned with overall future space mission goals and the facilities for their achievement. Present Ground Receiving Sites are documented in the 6 December 1966 report. The final report will contain a refinement of this data and give criteria for future receiving systems.

- The basis for system design criteria is found in the remaining technical sections. They are: Communication Theory, Transmitting Power Sources, Detectors, Optical Modulators, Acquisition and Tracking, Radio Frequency Antennas, Optics, Spacecraft Prime Power Generation, Background Radiation and Atmospheric Attenuation, and Heat Transfer Systems.

In this sixth quarterly report of "Parametric Analysis of Microwave and Laser Systems for Communications and Tracking" the Heat Radiator Section has been updated. It completely replaces the earlier edition dated 6 February 1966. In addition, several Appendices of the Methodology have been revised and replace earlier editions dated 6 December 1966.

1.2 REFERENCE DATA FORMAT

Each Reference Data Section is formed of six basic subsections. They are:

- Introduction
- Theory
- Performance
- Burden Relationships
- Nomenclature
- References

Each subsection of this basic structure is used in the component technology sections. However, some sections are not completely amenable to this organization of material and variations are allowed. The intent of the subsections is as follows.

1.2.1 Introduction

This subsection introduces the material of the section. The status of the section in relation to its ultimate development may be noted.

1.2.2 Theory

This subsection is designed to introduce the reader to the theory of the technological area being discussed. Basic relationships are given but extensive derivations are avoided. The theory is presented as a guide for using the material of the section and as a means to project parameter capabilities.

1.2.3 Performance

This subsection contains the documented state of the art of the technology. It lists new variants of the technology and tabulated parameters and performance.

1.2.4 Burden Relationships

This subsection contains the parametric relationships of the section technology. Of particular concern is the relationship of parameter values as a function of weight, cost, size, etc. Ancillary equipment required by the technology are also described in this subsection.

1.2.5 Nomenclature

A nomenclature subsection was introduced in the 6 June 1966 issue of "Reference Data for Advanced Space Communication and Tracking Systems." It is intended to apply only to the section of which it is a part. It will form the basis for a complete and uniform nomenclature for the entire volume.

1.2.6 References

This subsection lists references used in the section proper. The references are not intended as an extensive bibliography but rather to direct the reader to the source of the documented material.

1.3 FRONT MATTER

The Table of Contents, List of Illustrations and List of Tables is complete for the entire volume of "Reference Data for Advanced Space Communication and Tracking Systems." The date of last issue for each section is given in the Table of Contents. Text material for sections not updated in this issue may be found in the second issue dated 6 June 1966, Report Number P66-135, in the third issue dated 6 September 1966, Report Number P66-213, and in the fourth dated 6 December 1966, Report Number P67-09. (Note that the first issue dated 6 February 1966, Report Number P66-16, has now been completely replaced by subsequent editions.)

APPENDIX A2. 1
NOMENCLATURE

Computer Symbol	Text Symbol		Description
			System Parameters
PT	P_T	=	transmitter power
DT	d_T	=	transmitter aperture diameter
DR	d_R	=	receiver aperture diameter
THER	θ_R	=	receiver field of view
RB	R_B	=	information rate
PTϕ	P_{TO}	=	optimum value of P_T
DTϕ	d_{TO}	=	optimum value of d_T
DRϕ	d_{RO}	=	optimum value of d_R
THERϕ	θ_{RO}	=	optimum value of θ_R
PTI	P_{TI}	=	initial program value of P_T
DTI	d_{TI}	=	initial program value of d_T
DRI	d_{RI}	=	initial program value of d_R
THRI	θ_{RI}	=	initial program value of θ_R
PTB	P_{TB}	=	limit value of P_T
DTB	d_{TB}	=	limit value of d_T
DRB	d_{RB}	=	limit value of d_R
THERB	θ_{RB}	=	limit value of θ_R
PTM	P_{TM}	=	fixed value of P_T (= O for no constraint)
DTM	d_{TM}	=	fixed value of d_T (= O for no constraint)
DRM	d_{RM}	=	fixed value of d_R (= O for no constraint)
THERM	θ_{RM}	=	fixed value of θ_R (= O for no constraint)

Computer Symbol	Text Symbol		Description
			<u>System Costs</u>
CDT	C_{d_T}	=	transmitter antenna cost
CDR	C_{d_R}	=	receiver antenna cost
CAT	C_{AT}	=	transmitter acquisition and track equipment fabrication cost independent of transmitter beamwidth
CTHT	C_{θ_T}	=	transmitter antenna fabrication cost
CTHR	C_{θ_R}	=	receiver antenna fabrication cost
CQT	C_{QT}	=	transmitter acquisition and track equipment cost
CNT	C_{NT}	=	transmitter acquisition and track equipment fabrication cost
CAR	C_{AR}	=	receiver acquisition and track equipment fabrication cost independent of receiver field of view
CQR	C_{QR}	=	receiver acquisition and track equipment cost
CNR	C_{NR}	=	receiver acquisition and track equipment fabrication cost
CFL	C_{FL}	=	transmitter fabrication cost
CPT	C_{P_T}	=	transmitter cost
CM	C_M	=	modulation equipment cost
CD	C_D	=	demodulation equipment cost
CFM	C_{FM}	=	modulation equipment fabrication cost
CFD	C_{FD}	=	demodulation equipment fabrication cost
CKT	C_{KT}	=	transmitter antenna fabrication cost independent of transmitter aperture diameter
CKR	C_{KR}	=	receiver antenna fabrication cost independent of receiver aperture diameter

Computer Symbol	Text Symbol		Description
CKH	C_{KH}	=	transmitter heat exchanger fabrication cost independent of transmitter power dissipation
CST	C_{ST}	=	transmitter power supply cost
CSR	C_{SR}	=	receiver power supply cost
CH	C_{H}	=	heat exchanger fabrication cost
CFT	C_{FT}	=	transmitter power supply fabrication cost
CFR	C_{FR}	=	receiver power supply fabrication cost
CKP	C_{KP}	=	transmitter fabrication cost independent of transmitter power
CKM	C_{KM}	=	modulation equipment fabrication cost independent of information rate
CKD	C_{KD}	=	demodulation equipment fabrication cost independent of information rate
CKE	C_{KE}	=	transmitter power supply fabrication cost independent of transmitter power requirement
CKF	C_{KF}	=	receiver power supply fabrication cost independent of receiver power requirement
CS	C_{S}	=	total system cost
CV	C_{V}	=	variable part of total system cost (optimization cost)
CFA	C_{FA}	=	fixed part of total transmitter cost
CFB	C_{FB}	=	fixed part of total receiver cost
CG	C_{G}	=	cost of transmitter, transmitter power supply, and transmitter heat exchanger which is dependent upon transmitter power

Computer Symbol	Text Symbol		Description
CT	C_T	=	cost of transmitter antenna, transmitter acquisition and track equipment, and associated power supply which is dependent upon transmitter aperture diameter
CQ	C_Q	=	cost of receiver acquisition and track equipment which is dependent upon receiver field of view
CR	C_R	=	cost of receiver antenna, receiver acquisition and track equipment, and associated power supply which is dependent upon receiver aperture diameter
CFA	C_{FA}	=	total transmitter fabrication costs for optimum system parameters
CFB	C_{FB}	=	total receiver fabrication costs for optimum system parameters
CA	C_A	=	total transmitter cost for optimum system parameters
CB	C_{BO}	=	total receiver cost for optimum system parameters
CTϕ	C_{TO}	=	value of C_T for optimum system parameters
CRϕ	C_{RO}	=	value of C_R for optimum system parameters
CGϕ	C_{GO}	=	value of C_G for optimum system parameters
CQϕ	C_{QO}	=	value of C_Q for optimum system parameters
CVϕ	C_{VO}	=	value of C_V for optimum system parameters

Computer Symbol	Text Symbol		Description
			System Weights
WDT	W_{d_T}	=	transmitter antenna weight
WDR	W_{d_R}	=	receiver antenna weight
WQT	W_{QT}	=	transmitter acquisition and track equipment weight
WBT	W_{BT}	=	transmitter acquisition and track equipment weight independent of transmitter beamwidth
WQR	W_{QR}	=	receiver acquisition and track equipment weight
WBR	W_{BR}	=	receiver acquisition and track equipment weight independent of receiver field of view.
WT	W_T	=	transmitter weight
WM	W_M	=	modulation equipment weight
WD	W_D	=	demodulation equipment weight
WSR	W_{SR}	=	receiver power supply weight
WST	W_{ST}	=	transmitter power supply weight
WH	W_H	=	transmitter heat exchanger weight
WKT	W_{KT}	=	transmitter antenna weight independent of transmitter aperture diameter
WKR	W_{KR}	=	receiver antenna weight independent of receiver aperture diameter
WKP	W_{KP}	=	transmitter weight independent of transmitter power
WKH	W_{KH}	=	transmitter heat exchanger weight independent of transmitter power dissipation

Computer Symbol	Text Symbol		Description
WKM	W_{KM}	=	modulation equipment weight independent of information rate
WKD	W_{KD}	=	demodulation equipment weight independent of information rate
WKE	W_{KE}	=	transmitter power supply weight independent of transmitter power requirement
WKF	W_{KF}	=	receiver power supply weight independent of receiver power requirement
WA	W_A	=	total transmitter weight for optimum system parameters
WB	W_B	=	total receiver weight for optimum system parameters

Computer Symbol	Text Symbol		Description
			System Power Requirements
PQT	P_{QT}	=	transmitter acquisition and track equipment power requirement
PQR	P_{QR}	=	receiver acquisition and track equipment power requirement
PPT	P_{PT}	=	transmitter power requirement
PM	P_M	=	modulation equipment power requirement
PD	P_D	=	demodulation equipment power requirement
PST	P_{ST}	=	transmitter power supply power requirement
PSR	P_{SR}	=	receiver power supply power requirement
PA	P_A	=	total transmitter power requirement for optimum system parameters
PB	P_B	=	total receiver power requirement for optimum system parameters

Computer Symbol	Text Symbol		Description
			<u>System Constants of Proportionality</u>
KDT	K_{d_t}	=	constant relating transmitter antenna weight to transmitter aperture diameter
KTHT	K_{θ_T}	=	constant relating transmitter antenna fabrication cost to transmitter aperture diameter
KS	K_S	=	cost per unit weight for spaceborne equipment
KDR	K_{d_R}	=	constant relating receiver antenna weight to receiver aperture diameter
KTHR	K_{θ_R}	=	constant relating receiver antenna fabrication cost to receiver aperture diameter
KAT	K_{AT}	=	constant relating transmitter tracking equipment fabrication cost to transmitter beamwidth
KWAT	$K_{W_{AT}}$	=	constant relating transmitter tracking equipment weight to transmitter antenna weight
KPQT	$K_{P_{QT}}$	=	constant relating transmitter acquisition and track equipment power requirement to equipment weight
KAR	K_{AR}	=	constant relating receiver tracking equipment fabrication cost to receiver field of view
KWAR	$K_{W_{AR}}$	=	constant relating receiver tracking equipment weight to receiver antenna weight
KPQR	$K_{P_{QR}}$	=	constant relating receiver acquisition and track equipment power requirement to equipment weight
KWT	K_{W_T}	=	constant relating transmitter weight to transmitter power
KPT	K_{P_T}	=	constant relating transmitter fabrication cost to transmitter power

Computer Symbol	Text Symbol		Description
KPM	K_{P_M}	=	constant relating modulation equipment power requirement to equipment weight
KPD	K_{P_D}	=	constant relating demodulation equipment power requirement to equipment weight
KST	K_{ST}	=	constant relating transmitter power supply fabrication cost to power requirement
KWST	$K_{W_{ST}}$	=	constant relating transmitter power supply weight to power requirement
KSR	K_{SR}	=	constant relating receiver power supply fabrication cost to power requirement
KWR	K_{WR}	=	constant relating receiver power supply weight to power requirement
KH	K_H	=	constant relating transmitter heat exchanger fabrication cost to transmitter power dissipation
KX	K_X	=	constant relating transmitter heat exchanger weight to transmitter power dissipation
KM	K_M	=	constant relating modulation equipment weight to information rate
KFM	K_{FM}	=	constant relating modulation equipment fabrication cost to information rate
KD	K_D	=	constant relating demodulation equipment weight to information rate
KFD	K_{F_D}	=	constant relating demodulation equipment fabrication cost to information rate
KQT	K_{q_T}	=	constant defined in text
KMT	K_{m_T}	=	constant defined in text

Computer Symbol	Text Symbol		Description
KNT	K_{n_T}	=	constant defined in text
KQR	K_{q_R}	=	constant defined in text
KMR	K_{m_R}	=	constant defined in text
KNR	K_{n_R}	=	constant defined in text
KGT	K_{g_T}	=	constant defined in text
KHT	K_{h_T}	=	constant defined in text
KJT	K_{j_T}	=	constant defined in text
QT	q_T	=	constant
MT	m_T	=	constant
NT	n_T	=	constant
QR	q_R	=	constant
MR	m_R	=	constant
NR	n_R	=	constant
GT	g_T	=	constant
HT	h_T	=	constant
KN	K_N	=	SNR constant for shot noise limited direct and heterodyne detection optical receiver
K	K	=	SNR constant for shot noise limited direct detection optical receiver
KT	K_M	=	SNR constant for thermal noise limited direct detection optical receiver
KR	K_R	=	SNR constant for radio receiver
KE	k_e	=	transmitter power efficiency

Computer Symbol	Text Symbol		Description
R	R	=	transmission range
LMBDI	λ_i	=	receiver input filter bandwidth in wavelength units
	B_O	=	receiver output filter bandwidth in frequency units
	Λ	=	optimization dummy variable
	Q	=	optimization dummy variable
	G	=	detector current gain
	I_D	=	detector dark current
TAUT	τ_t	=	transmitter transmissivity
TAUR	τ_r	=	receiver transmissivity
TAUA	τ_a	=	atmospheric transmissivity
ETA	η	=	detector quantum efficiency
QB	Q_B	=	background radiation photon spectral radiance
LAMBDA	λ	=	transmission wavelength
RL	R_L	=	receiver load resistance
SMK	k	=	Boltzsmann's constant
H	h	=	Planck's constant
Q	q	=	electronic charge
C	c	=	velocity of light
TE	T_e	=	receiver temperature
USBQ	$(\mu_{S,B})_{Req}$	=	number of signal photoelectrons required per bit
UNBQ	$(\mu_{N,B})_{Req}$	=	number of noise photoelectrons required per bit

Computer Symbol	Text Symbol		Description
USS	$\mu_{S,S}$	=	number of signal photoelectrons per second
UNS	$\mu_{N,S}$	=	number of noise photoelectrons per second
SN	$\left(\frac{S}{N}\right)$	=	receiver output power signal-to-noise ratio
RB	R_B	=	information rate in bits per second
CP	C_P	=	constant relating shot noise powers due to signal and background radiation

APPENDIX A2.2
INPUT DATA PROGRAM

FUNCTION

The function of the input data program is to provide parametric computer plots of the system burdens as a function of the major system parameters.

DESCRIPTION

Exhibit A2.2-1 is a flow chart of the Input Data Program. The input independent variables are listed below:

transmission wavelength (microns) λ $[\lambda_1, \ldots, \lambda 5]$
information rate (bits per second) R_B $[10^1, 10^2, \ldots, 10^{10}]$
transmitter aperture diameter (cm) d_T [1, 2, 5, 10, 20, 50, 100]
receiver aperture diameter (cm) d_R [10, 20, 50, 100, 200, 500, 1000]
transmitter power (watts) P_T [1, 2, 5, 10, 20, 50, 100]
receiver field of view (rad.) θ_R $[0.1 \times 10^3,\ 0.2 \times 10^{-3},\ 0.5 \times 10^{-3},\ 1.0 \times 10^{-3}]$

Exhibit A2.2-2 contains a typical listing of the required system burdens data. Exhibit A2.2-3 contains a listing of the plots generated by the computer. Exhibit A2.2-4 contains a listing of the Fortran IV Input Data Program.

EXHIBIT A2.2-1

OPTIMIZATION METHODOLOGY INPUT DATA PROGRAM

START

READ INPUT INDEPENDENT VARIABLES

READ AND PRINT SYSTEM BURDENS DATA

COMPUTE AND PLOT SYSTEM WEIGHT BURDENS

COMPUTE AND PLOT SYSTEM POWER BURDENS

COMPUTE AND PLOT SYSTEM FABRICATION COST BURDENS

COMPUTE AND PLOT SYSTEM COMPONENT COST BURDENS

COMPUTE AND PLOT SYSTEM COST VARIABLES

EXIT

EXHIBIT A2.2-2

SYSTEM BURDENS INPUT DATA

Component	Parameter	Unit	Wavelength 0.51μ	0.63μ	0.84μ	3.39μ	10.6μ
Transmitter Antenna	$K_{\theta T}$	$[1]	14	–	–	–	–
	K_{dT}	lb[1]	0.01	–	–	–	–
	C_{KT}	$	2×10^4	–	–	–	–
	W_{KT}	lb	25	–	–	–	–
	m_T	–	2	–	–	–	–
	n_T	–	2	–	–	–	–
Receiver Antenna	$K_{\theta R}$	$[2]	8.75	–	–	–	–
	K_{dR}	lb[3]	2.3×10^{-2}	–	–	–	–
	C_{KR}	$	2.5×10^4	–	–	–	–
	W_{KR}	lb	20	–	–	–	–
	m_R	–	2	–	–	–	–
	n_R	–	2	–	–	–	–
Transmitter Acquisition and Track System	K_{AT}	$[4]	80	–	–	–	–
	K_{WAT}	lb[1]	2.22	–	–	–	–
	K_{PQT}	watt/lb	0.66	–	–	–	–
	C_{AT}	$	10,000	–	–	–	–
	W_{BT}	lb	460	–	–	–	–
	q_T	–	2	–	–	–	–
Receiver Acquisition and Track System	K_{AR}	$[2]	80	–	–	–	–
	K_{WAR}	lb[3]	2.22	–	–	–	–
	K_{PQR}	watt/lb	0.66	–	–	–	–
	C_{AR}	$	10,000	–	–	–	–
	W_{BR}	lb	350	–	–	–	–
	q_R	–	2	–	–	–	–
Transmitter	K_{PT}	$[5]	5000	3200	100	27,700	1.43
	K_{WT}	lb[5]	400	2000	10	5900	2
	K_H	$/watt	10	–	–	–	–
	K_X	lb/watt	0.07	–	–	–	–
	k_e	–	1×10^{-3}	2×10^{-3}	0.1	4×10^{-4}	0.1
	C_{KP}	$	5000	2000	2000	2000	2000
	C_{KH}	$	0	–	–	–	–
	W_{KP}	lb	100	100	25	100	25
	W_{KH}	lb	0	–	–	–	–
	P_{KT}	watt	10	–	–	–	–
	q_T	–	2	–	–	–	–
	h_T	–	1	–	–	–	–

Component	Parameter	Unit	Wavelength 0.51μ	0.63μ	0.84μ	3.39μ	10.6μ
Modulation Equipment	K_{FM}	$/bit	7.5×10^{-5}	7.5×10^{-5}	0	1.5×10^{-4}	0
	K_M	lb/bit	5×10^{-8}	5×10^{-8}	0	9×10^{-8}	0
	K_{PM}	watt/lb	3.33	–	–	–	–
	C_{KM}	$	7500	7500	7500	10^4	3×10^4
	W_{KM}	lb	5	5	5	7.5	20
Demodulation Equipment	K_{FD}	$/bit	5×10^{-5}	5×10^{-5}	5×10^{-5}	10^{-4}	10^{-4}
	K_D	lb/bit	10^{-7}	10^{-7}	10^{-7}	2×10^{-7}	2×10^{-7}
	K_{PD}	watt/lb	3.33	–	–	–	–
	C_{KD}	$	15,000	15,000	15,000	25,000	27,500
	W_{KD}	lb	30	30	30	50	55
Transmitter Power Supply	K_{ST}	$/watt	1250	–	–	–	–
	K_{WST}	lb/watt	0.125	–	–	–	–
	C_{KE}	$	10^4	–	–	–	–
	W_{KE}	lb	10	–	–	–	–
Receiver Power Supply	K_{SR}	$/watt	250	–	–	–	–
	K_{WSR}	lb/watt	0.125	–	–	–	–
	C_{KF}	$	10^4	–	–	–	–
	W_{KF}	lb	10	–	–	–	–
General	K_S	$/lb	1640	–	–	–	–
	K_{gT}		5000	3200	100	27,700	1.43
	K_{nT}		6.5×10^5	3.28×10^6	1.64×10^4	9.67×10^6	3.28×10^3
	K_{jT}		1.59×10^6	8.0×10^5	1.57×10^4	4.0×10^6	1.57×10^4
	K_{mT}		14	–	–	–	–
	K_{nT}		74.1	–	–	–	–
	K_{qT}		1.57×10^6	1.27×10^6	9.5×10^5	2.36×10^5	7.55×10^4
	K_{mR}		8.75	–	–	–	–
	K_{nR}		8.42	–	–	–	–
	K_{qR}		80	–	–	–	–

[1] Per unit of d_T
[2] Per θ_R unit
[3] Per unit of d_P
[4] Per θ_T unit
[5] Per P_T unit

EXHIBIT A2. 2-3

INPUT DATA PROGRAM COMPUTER PLOTS

All plots versus transmission wavelength.

System Weight Burdens

W_{d_T}	vs	d_T	
W_{d_R}	vs	d_R	
W_{QT}	vs	d_T	
W_{QR}	vs	d_R	
W_T	vs	P_T	
W_H	vs	P_T	
W_M	vs	R_B	
W_D	vs	R_B	
W_{ST}	vs	P_T	$R_B = 10^8$, $d_T = 10$ cm
W_{ST}	vs	P_T	$R_B = 10^8$, $d_T = 20$ cm
W_{ST}	vs	P_T	$R_B = 10^8$, $d_T = 50$ cm
W_{SR}	vs	d_R	$R_B = 10^8$

System Power Burdens

P_{QT}	vs	d_T
P_{QR}	vs	d_R
P_{PT}	vs	P_T
P_M	vs	R_B
P_D	vs	R_B

EXHIBIT A2. 2-3 (continued)

System Fabrication Cost Burdens

C_{θ_T}	vs	d_T	
C_{θ_R}	vs	d_R	
C_{NT}	vs	d_T	
C_{NR}	vs	θ_R	
C_{FL}	vs	P_T	
C_H	vs	P_T	
C_{FM}	vs	R_B	
C_{FD}	vs	R_B	
C_{FT}	vs	P_T	$R_B = 10^8$, $d_T = 10$ cm
C_{FT}	vs	P_T	$R_B = 10^8$, $d_T = 20$ cm
C_{FT}	vs	P_T	$R_B = 10^8$, $d_T = 50$ cm
C_{FR}	vs	d_R	$R_B = 10^8$

System Component Cost Burdens

C_{d_T}	vs	d_T	
C_{d_R}	vs	d_R	
C_{QT}	vs	d_T	
C_{QR}	vs	d_R	
C_{P_T}	vs	P_T	
C_M	vs	R_B	
C_D	vs	R_B	
C_{ST}	vs	P_T	$R_B = 10^8$, $d_T = 10$ cm
C_{ST}	vs	P_T	$R_B = 10^8$, $d_T = 20$ cm

EXHIBIT A2. 2-3 (continued)

C_{ST}	vs	P_T	$R_B = 10^8$, $d_T = 50$ cm
C_{SR}	vs	d_R	$R_B = 10^8$

System Cost Variables

C_T vs d_T

C_R vs d_R

C_G vs P_T

C_Q vs θ_R

EXHIBIT A2.2-4

```
$JOB    CF        56030,2113A,01140,5,1000           C.E.RADFORD
$IBJOB CER        GO,MAP
$IBFTC MAIN       LIST,DECK
      COMMON /CURVE / LAM(10), KE(10), DT(10), THER(10), PL(10), DR(10)
     *       /FOFDT / WDT(10), WQT(10), PQT(10), CTHT(10), CNT(10),
     *                CDT(10), CQT(10),  CT(10)
     *       /FOFDR / WDR(I0), WQR(10), WSR(10), PQR(10), CTHR(10),
     *                CFR(10), CDR(10), CQR(10), CSR(10),   CR(10),
     *                BD(10)
     *       /FOFPL /  WT(10),  WH(10), WST1(10), WST2(10), WST3(10),
     *                PPT(10), CFL(10), CFT1(10), CFT2(10), CFT3(10),
     *                 CG(10), CH(10),CPT(10),CST1(10),CST2(10),CST3(10)
     *       /FOFBD /  WM(10),  WD(10),   PM(10),   PD(10),  CFM(10),
     *                CFD(10),  CM(10),   CD(10)
     *       /FOFTHR/ CNR(10), CTH(10)
     *       /FREQ  / NOLAM, NODT, NOTHR, NOPL, NODR, NOBD
      COMMON /TANTNA/ KTHT,  KDT,  CKT,  WKT,   MT,   NT
     *       /RANTNA/ KTHR,  KDR,  CKR,  WKR,   MR,   NR
     *       /TACTRS/  KAT, KWAT, KPQT,  CAT,  CTT,  WBT,   QT
     *       /RACTRS/  KAR, KWAR, KPQR,  CAR,  CTR,  WBR,   QR
     *       /XMITER/  KPT(10), KWT(10), KH, KX, CKP(10), CKH,
     *                 WKP, WKH, PKT, GT, HT
     *       /MOD   /  KFM(10), KM(10), KPM, CKM(10), WKM(10)
     *       /DMOD  /  KFD(10), KD(10), KPD, CKD(10), WKD(10)
     *       /TPOWER/  KST, KWST, CKE, WKE
     *       /RPOWER/  KSR, KWSR, CKF, WKF
     *       /GEN   /  KS
 1000 FORMAT( 1H1 //// )
   10 CONTINUE
         CALL INPUT
      DO 20I = 1,NOLAM
      WRITE( 2,1000 )
         CALL COST( I )
         CALL OUTPUT( I )
   20 CONTINUE
      GO TO 10
      END
$IBFTC INPUT   DECK
      SUBROUTINE INPUT
      REAL KE, KTHT, KDT, MT, NT, KTHR, KDR, MR, NR, KAT, KWAT, KPQT,
     *     KAR, KWAR, KPQR, KPT, KWT, KH, KX, KFM, KM, KPM, KFD, KD, KPD,
     *     KST, KWST, KSR, KWSR, KS, LAM
      COMMON /CURVE / LAM(10), KE(10), DT(10), THER(10), PL(10), DR(10)
     *       /FOFDT / WDT(10), WQT(10), PQT(10), CTHT(10), CNT(10),
     *                CDT(10), CQT(10),  CT(10)
     *       /FOFDR / WDR(10), WQR(10), WSR(10), PQR(10), CTHR(10),
     *                CFR(10), CDR(10), CQR(10), CSR(10),   CR(10),
     *                BD(10)
     *       /FOFPL /  WT(10),  WH(10), WST1(10), WST2(10), WST3(10),
     *                PPT(10), CFL(10), CFT1(10), CFT2(10), CFT3(10),
     *                 CG(10), CH(10),CPT(10),CST1(10),CST2(10),CST3(10)
     *       /FOFBD /  WM(10),  WD(10),   PM(10),   PD(10),  CFM(10),
     *                CFD(10),  CM(10),   CD(10)
     *       /FOFTHR/ CNR(10), CTH(10)
     *       /FREQ  / NOLAM, NODT, NOTHR, NOPL, NODR, NOBD
      COMMON /TANTNA/ KTHT,  KDT,  CKT,  WKT,   MT,   NT
     *       /RANTNA/ KTHR,  KDR,  CKR,  WKR,   MR,   NR
```

EXHIBIT A2.2-4 (continued)

```
     *         /TACTRS/  KAT, KWAT, KPQT,  CAT,  CTT,  WBT,   QT
     *         /RACTRS/  KAR, KWAR, KPQR,  CAR,  CTR,  WBR,   QR
     *         /XMITER/  KPT(10), KWT(10), KH, KX, CKP(10), CKH,
     *                   WKP, WKH, PKT, GT, HT
     *         /MOD   /  KFM(10), KM(10), KPM, CKM(10), WKM(10)
     *         /DMOD  /  KFD(10), KD(10), KPD, CKD(10), WKD(10)
     *         /TPOWER/  KST, KWST, CKE, WKE
     *         /RPOWER/  KSR, KWSR, CKF, WKF
     *         /GEN   /  KS
2000  FORMAT( 5I15 )
2010  FORMAT( 5E15.7 )
      READ( 1,2000 ) NOLAM, NODT, NOTHR, NOPL, NODR, NOBD
      READ( 1,2010 ) (  LAM(I), I= 1,NOLAM )
      READ( 1,2010 ) (   KE(I), I= 1,NOLAM )
      READ( 1,2010 ) (  KPT(I), I= 1,NOLAM )
      READ( 1,2010 ) (  KWT(I), I= 1,NOLAM )
      READ( 1,2010 ) (  CKP(I), I= 1,NOLAM )
      READ( 1,2010 ) (  KFM(I), I= 1,NOLAM )
      READ( 1,2010 ) (   KM(I), I= 1,NOLAM )
      READ( 1,2010 ) (  CKM(I), I= 1,NOLAM )
      READ( 1,2010 ) (  WKM(I), I= 1,NOLAM )
      READ( 1,2010 ) (  KFD(I), I= 1,NOLAM )
      READ( 1,2010 ) (   KD(I), I= 1,NOLAM )
      READ( 1,2010 ) (  CKD(I), I= 1,NOLAM )
      READ( 1,2010 ) (  WKD(I), I= 1,NOLAM )
      READ( 1,2010 ) (   DT(I), I= 1,NODT  )
      READ( 1,2010 ) ( THER(I), I= 1,NOTHR )
      READ( 1,2010 ) (   PL(I), I= 1,NOPL  )
      READ( 1,2010 ) (   DR(I), I= 1,NODR  )
      READ( 1,2010 ) (   BD(I), I= 1,NOBD  )
      READ( 1,2010 )   KTHT,  KDT,  CKT,  WKT,   MT,
     *                   NT, KTHR,  KDR,  CKR,  WKR,
     *                   MR,   NR,  KAT, KWAT, KPQT,
     *                  CAT,  CTT,  WBT,   QT,  KAR,
     *                 KWAR, KPQR,  CAR,  CTR,  WBR,
     *                   QR,   KH,   KX,  CKH,  WKP,
     *                  WKH,  PKT,   GT,   HT,  KPM,
     *                  KPD,  KST, KWST,  CKE,  WKE,
     *                  KSR, KWSR,  CKF,  WKF,   KS
      CALL PDUMP( LAM(1), KS, 1 )
      RETURN
      END
$IBFTC COST    LIST,REF,DECK
      SUBROUTINE COST( K )
      REAL KQT, KMT, KNT, KMR, KNR, KQR, KGT, KHT, KJT
      REAL KE, KTHT, KDT, MT, NT, KTHR, KDR, MR, NR, KAT, KWAT, KPQT,
     *    KAR, KWAR, KPQR, KPT, KWT, KH, KX, KFM, KM, KPM, KFD, KD, KPD,
     *    KST, KWST, KSR, KWSR, KS, LAM
      COMMON /CURVE / LAM(10), KE(10), DT(10), THER(10), PL(10), DR(10)
     *       /FOFDT / WDT(10), WQT(10), PQT(10), CTHT(10), CNT(10),
     *                CDT(10), CQT(10),  CT(10)
     *       /FOFDR / WDR(10), WQR(10), WSR(10), PQR(10), CTHR(10),
     *                CFR(10), CDR(10), CQR(10), CSR(10),   CR(10),
     *                BD(10)
     *       /FOFPL /  WT(10),  WH(10), WST1(10), WST2(10), WST3(10),
     *                PPT(10), CFL(10), CFT1(10), CFT2(10), CFT3(10),
     *                 CG(10), CH(10),CPT(10),CST1(10),CST2(10),CST3(10)
```

EXHIBIT A2. 2-4 (continued)

```
     *       /FOFBD /  WM(10),  WD(10),  PM(10),   PD(10),  CFM(10),
     *                 CFD(10),  CM(10),   CD(10)
     *       /FOFTHR/ CNR(10), CTH(10)
     *       /FREQ  / NOLAM, NODT, NOTHR, NOPL, NODR, NOBD
      COMMON /TANTNA/ KTHT,  KDT,  CKT,  WKT,   MT,   NT
     *       /RANTNA/ KTHR,  KDR,  CKR,  WKR,   MR,   NR
     *       /TACTRS/  KAT, KWAT, KPQT,  CAT,  CTT,  WBT,    QT
     *       /RACTRS/  KAR, KWAR, KPQR,  CAR,  CTR,  WBR,    QR
     *       /XMITER/  KPT(10), KWT(10), KH, KX, CKP(10), CKH,
     *                 WKP, WKH, PKT, GT, HT
     *       /MOD   /  KFM(10), KM(10), KPM, CKM(10), WKM(10)
     *       /DMOD  /  KFD(10), KD(10), KPD, CKD(10), WKD(10)
     *       /TPOWER/  KST, KWST, CKE, WKE
     *       /RPOWER/  KSR, KWSR, CKF, WKF
     *       /GEN   /  KS
      EQUIVALENCE ( KMT,KTHT), ( KMR,KTHR), ( KQR,KAR)
      KGT = KPT(K)
      KQT = KAT / LAM(K) **QT
      KNT = KDT * ( KS *( 1.+KWAT ) + KPQT * KWAT * ( KST + KS * KWST ))
      KNR = KDR * ( KS *( 1.+KWAR ) + KPQR * KWAR * ( KSR + KS * KWSR ))
      KHT = KS * KWT( K )
      KJT = KS * ( KWST/ KE(K) + KX * ( 1./KE(K)-1. )) + KST /KE(K)
     *    + KH * ( 1./KE(K)-1. )
      DO 10I = 1,NODT
            DTNT = DT(I) **NT
         WDT(I) = KDT * DTNT + WKT
         WQT(I) = WBT + KWAT * KDT * DTNT
         PQT(I) = KPQT * ( WBT + KWAT * KDT * DTNT )
        CTHT(I) = KTHT * DT(I) **MT + CKT
         CNT(I) = CAT + KAT / LAM(K) **QT * DT(I) **QT
         CDT(I) = CTHT + KS * WDT(I)
         CQT(I) = CAT + CTT + KS * WQT(I)
          CT(I) = KQT * DT(I) **QT + KMT * DT(I) **MT + KNT * DTNT
10    CONTINUE
      DO 20I = 1,NODR
            DRNR = DR(I) **NR
         WDR(I) = KDR * DRNR + WKR
         WQR(I) = WBR + KWAR * KDR * DRNR
            HOLD= KPD*( KD(K) *1.E8 + WKD(K) ) + KPQR * ( WBR + KWAR *
     *              KDR * DRNR )
         WSR(I) = KWSR * HOLD + WKF
         PQR(I) = KPQR * ( WBR + KWAR * KDR * DRNR )
        CTHR(I) = KTHR * DR(I) **MR + CKR
         CFR(I) = KSR * HOLD + CKF
         CDR(I) = CTHR(I) + KS * WDR(I)
         CQR(I) = CAR + CTR + KS * WQR(I)
         CSR(I) = CFR(I) + KS * WSR(I)
          CR(I) = KMR * DR(I) **MR + KNR * DRNR
20    CONTINUE
      DO 30I = 1,NOPL
          WT(I) = KWT(K) * PL(I) **HT + WKP
          WH(I) = KX *( 1./KE(K)-1. ) * PL(I) + WKH
        WST1(I) = KWST * ( KPM * KM(K) *1.E8 + PL(I) / KE(K) + KPQT *
     *            ( WBT + KWAT * KDT * (10.) **NT ) ) + WKE
        WST2(I) = KWST * ( KPM * KM(K) *1.E8 + PL(I) / KE(K) + KPQT *
     *            ( WBT + KWAT * KDT * (20.) **NT ) ) + WKE
        WST3(I) = KWST * ( KPM * KM(K) *1.E8 + PL(I) / KE(K) + KPQT *
```

EXHIBIT A2.2-4 (continued)

```
     *           ( WBT + KWAT * KDT * (50.) **NT ) ) + WKE
        PPT(I) = PL(I) /KE(K) + PKT
        CFL(I) = KPT(K) * PL(I) **GT + CKP(K)
         CH(I) = KH * ( 1./KE(K)-1. ) * PL(I) + CKH
       CFT1(I) = KST * ( KPM * KM(K) * 1.E8 + PL(I)/KE(K) + KPQT *
     *           ( WBT + KWAT * KDT * (10.) **NT ) ) + CKE
       CFT2(I) = KST * ( KPM * KM(K) * 1.E8 + PL(I) /KE(K) + KPQT *
     *           ( WBT + KWAT * KDT * (20.) **NT ) ) + CKE
       CFT3(I) = KST * ( KPM * KM(K) * 1.E8 + PL(I) /KE(K) + KPQT *
     *           ( WBT + KWAT * KDT * (50.) **NT ) ) + CKE
        CPT(I) = CFL(I) + CH(J) + KS * ( WT(I)+WH(I) )
       CST1(I) = CFT1(I) + KS * WST1(I)
       CST2(I) = CFT2(I) + KS * WST2(I)
       CST3(I) = CFT3(I) + KS * WST3(I)
         CG(I) = KGT * PL(I) **GT + KHT * PL(I) **HT + KJT * PL(I)
   30 CONTINUE
      DO 40I = 1,NOBD
         WM(I) = KM(K) * BD(I) + WKM(K)
         WD(I) = KD(K) * BD(I) + WKD(K)
         PM(I) = KPM *(KM(K) * BD(I) + WKM(K) )
         PD(I) = KPD * ( KD(K) * BD(I) + WKD(K) )
        CFM(I) = KFM(K) * BD(I) + CKM(K)
        CFD(I) = KFD(K) * BD(I) + CKD(K)
         CM(I) = CFM(I) + KS * WM(I)
         CD(I) = CFD(I) + KS * WD(I)
   40 CONTINUE
      DO 50I = 1,NOTHR
        CNR(I) = CAR + KAR / THER(I) **QR
        CTH(I) = KQR / THER(I) **QR
   50 CONTINUE
      RETURN
      END
$IBFTC OUTPUT  LIST,DECK
      SUBROUTINE OUTPUT( K )
      COMMON /CURVE / LAM(10), KE(10), DT(10), THER(10), PL(10), DR(10)
     *       /FOFDT / WDT(10), WQT(10), PQT(10), CTHT(10), CNT(10),
     *                CDT(10), CQT(10),  CT(10)
     *       /FOFDR / WDR(10), WQR(10), WSR(10), PQR(10), CTHR(10),
     *                CFR(10), CDR(10), CQR(10), CSR(10),  CR(10),
     *                BD(10)
     *       /FOFPL /  WT(10),  WH(10), WST1(10), WST2(10), WST3(10),
     *                PPT(10), CFL(10), CFT1(10), CFT2(10), CFT3(10),
     *                 CG(10), CH(10),CPT(10),CST1(10),CST2(10),CST3(10)
     *       /FOFBD /  WM(10),  WD(10),   PM(10),   PD(10),  CFM(10),
     *                CFD(10),  CM(10),   CD(10)
     *       /FOFTHR/ CNR(10), CTH(10)
     *       /FREQ  / NOLAM, NODT, NOTHR, NOPL, NODR, NOBD
      COMMON /TANTNA/ KTHT,  KDT,  CKT,  WKT,   MT,   NT
     *       /RANTNA/ KTHR,  KDR,  CKR,  WKR,   MR,   NR
     *       /TACTRS/  KAT, KWAT, KPQT,  CAT,  CTT,  WBT,   QT
     *       /RACTRS/  KAR, KWAR, KPQR,  CAR,  CTR,  WBR,   QR
     *       /XMITER/  KPT(10), KWT(10), KH, KX, CKP(10), CKH,
     *                 WKP, WKH, PKT, GT, HT
     *       /MOD   /  KFM(10), KM(10), KPM, CKM(10), WKM(10)
     *       /DMOD  /  KFD(10), KD(10), KPD, CKD(10), WKD(10)
     *       /TPOWER/  KST, KWST, CKE, WKE
     *       /RPOWER/  KSR, KWSR, CKF, WKF
```

EXHIBIT A2. 2-4 (continued)

```
     *        /GEN    /  KS
      DIMENSION HOLD(10), HOLD1(10), HOLD2(10), HOLD3(10)
 3000 FORMAT(14X 2HDT 18X 3HWDT 17X 3HWQT 17X 3HPQT 17X 4HCTHT 16X 3HCNT
     *//(/E23.8, 5E20.8) )
 3010 FORMAT(//14X2HDT18X 3HCDT 17X 3HCQT 18X 2HCT //(/ E23.8, 3E20.8) )
 3020 FORMAT(//14X2HDR18X 3HWDR 17X 3HWQR 17X 3HWSR 17X 3HPQR 17X 4HCTHR
     *// (/ E23.8, 5E20.8) )
 3030 FORMAT(//14X2HDR18X 3HCFR 17X 3HCDR 17X 3HCQR 17X 3HCSR 18X 2HCR
     *// (/ E23.8, 5E20.8) )
 3040 FORMAT(//14X2HPL18X 2HWT 18X 2HWH 18X 4HWST1 16X 4HWST2 16X 4HWST3
     *// (/ E23.8,5E20.8) )
 3050 FORMAT(//14X2HPL18X 3HPPT 17X 3HCFL 17X 2HCH 18X 4HCFT1 16X 4HCFT2
     *// (/ E23.8,5E20.8 ) )
 3060 FORMAT(//14X2HPL18X 4HCFT3 16X 3HCPT 17X 4HCST1 16X 4HCST2 16X
     *     4HCST3  // (/ E23.8, 5E20.8 ) )
 3070 FORMAT(//14X2HPL18X 2HCG  // (/E23.8,E20.8) )
 3080 FORMAT(//14X2HBD18X 2HWM 18X 2HWD 18X 2HPM 18X 2HPD //(/E23.8,
     *     4E20.8) )
 3090 FORMAT(//14X2HBD18X 3HCFM 17X 3HCFD 17X 2HCM 18X 2HCD //
     *( / E23.8, 4E20.8) )
 3100 FORMAT(//14X4HTHER16X 3HCNR 17X 3HCTH //(/E23.8,2E20.8) )
 3110 FORMAT( /// 14X 3HLAM 17X 3HKPT 17X 3HKWT 17X 3HKFD 17X 2HKE
     *      18X 3HCKP // E23.8, 5E20.8 /// 14X 2HKD 18X 3HKFM 17X 2HKM
     *      18X 3HCKD 17X 3HCKM 17X 3HWKM // E23.8, 5E20.8 /// 14X 4HWKD=
     *        E16.8 )
      WRITE( 2,3110 ) LAM(K), KPT(K), KWT(K), KFD(K), KE(K), CKP(K),
     *                  KD(K), KFM(K),  KM(K), CKD(K), CKM(K), WKM(K),
     *                  WKD(K)
      WRITE( 2,3000 ) ( DT(I), WDT(I), WQT(I), PQT(I), CTHT(I),
     *                  CNT(I), I = 1,NODT )
      WRITE( 2,3010) ( DT(I), CDT(I), CQT(I), CT(I), I = 1,NODT )
      WRITE( 2,3020) ( DR(I), WDR(I), WQR(I), WSR(I), PQR(I), CTHR(I),
     *       I = 1,NODR )
      WRITE( 2,3030) ( DR(I), CFR(I), CDR(I), CQR(I), CSR(I), CR(I),
     *       I = 1,NODR )
      WRITE( 2,3040) ( PL(I), WT(I), WH(I), WST1(I), WST2(I), WST3(I),
     *       I = 1,NOPL )
      WRITE( 2,3050) ( PL(I), PPT(I), CFL(I), CH(I), CFT1(I), CFT2(I),
     *       I = 1,NOPL )
      WRITE( 2,3060) ( PL(I), CFT3(I), CPT(I), CST1(I), CST2(I), CST3(I)
     *     , I = 1,NOPL )
      WRITE( 2,3070) ( PL(I), CG(I), I= 1,NOPL )
      WRITE( 2,3080) ( BD(I), WM(I), WD(I), PM(I), PD(I), I = 1,NOBD )
      WRITE( 2,3090) ( BD(I), CFM(I), CFD(I), CM(I), CD(I),I=1,NOBD )
      WRITE( 2,3100) ( THER(I), CNR(I), CTH(I), I = 1,NOTHR )
      IF( K .GT. 1 ) RETURN
      DO 10I = 1,NODT
       HOLD(I) = DT(I)
      HOLD1(I) = DT(I)
   10 CONTINUE
      CALL CPLOT( 4,HOLD,20.,2HDT,NODT,WDT,8.,3HWDT,NODT,WQT,8.,3HWQT,
     *                         NODT,PQT,8.,3HPQT,NODT,CTHT,8.,4HCTHT)
      CALL CPLOT( 4,HOLD1,20.,2HDT,NODT,CNT,8.,3HCNT,NODT,CDT,8.,3HCDT,
     *                         NODT,CQT,8.,3HCQT,NODT,CT,8.,2HCT )
      DO 20I = 1,NODR
       HOLD(I) = DR(I)
      HOLD1(I) = DR(I)
```

```
 20   CONTINUE
      CALL CPLOT(5,HOLD,20.,2HDR,NODR,WDR,8.,3HWDR,NODR,WQR,8.,3HWQR,
     *                              NODR,WSR,8.,3HWSR,NODR,PQR,8.,3HPQR,
     *                              NODR,CTHR,8.,4HCTHR )
      CALL CPLOT(5,HOLD1,20.,2HDR,NODR,CFR,8.,3HCFR,NODR,CDR,8.,3HCDR,
     *                              NODR,CQR,8.,3HCQR,NODR,CSR,8.,3HCSR,
     *                              NODR,CR,8.,2HCR )
      DO 30I = 1,NOPL
       HOLD(I) = PL(I)
      HOLD1(I) = PL(I)
      HOLD2(I) = PL(I)
      HOLD3(I) = PL(I)
 30   CONTINUE
      CALL CPLOT(6,HOLD,20.,2HPL,NOPL,CFT1,8.,4HCFT1,NOPL,CFT2,8.,4HCFT2
     *                    .,NOPL,CFT3,8.,4HCFT3,NOPL,CST1,8.,4HCST1,
     *                      NOPL,CST2,8.,4HCST2,NOPL,CST3,8.,4HCST3 )
      CALL CPLOT(3,HOLD1,20.,2HPL,NOPL,WST1,8.,4HWST1,NOPL,WST2,8.,
     *                       4HWST2,NOPL,WST3,8.,4HWST3 )
      CALL CPLOT(4,HOLD2,20.,2HPL,NOPL,WT,8.,2HWT,NOPL,WH,8.,2HWH,
     *                              NOPL,CFL,8.,3HCFL,NOPL,CH,8.,2HCH )
      CALL CPLOT(3,HOLD3,20.,2HPL,NOPL,PPT,8.,3HPPT,NOPL,CPT,8.,3HCPT,
     *                              NOPL,CG,8.,2HCG )
      DO 40I = 1,NOBD
       HOLD(I) = BD(I)
      HOLD1(I) = BD(I)
 40   CONTINUE
      CALL CPLOT(4,HOLD,20.,2HBD,NOBD,WM,8.,2HWM,NOBD,WD,8.,2HWD,
     *                             NOBD,PM,8.,2HPM,NOBD,PD,8.,2HPD )
      CALL CPLOT(4,HOLD1,20.,2HBD,NOBD,CFM,8.,3HCFM,NOBD,CFD,8.,3HCFD,
     *                             NOBD,CM,8.,2HCM,NOBD,CD,8.,2HCD )
      DO 50I = 1,NOTHR
       HOLD(I) = THER
 50   CONTINUE
      CALL CPLOT(2,HOLD,20.,4HTHER,NOTHR,CNR,8.,3HCNR,NOTHR,CTH,8.,
     *        3HCTH )
      RETURN
      END
$DATA
            5               7               4               7               7
           10
        .51E-4          .63E-4          .84E-4         3.39E-4        10.6E-4
         1.E-3           2.E-3           1.E-4           4.E-4          1.E-1
          5.E3           3.2E3            1.E2          27.7E3           1.43
          400.           2.0E3            10.0           5.9E3             2.
          5.E3           2.0E3            2.E3           2.0E3           2.E3
        7.5E-5          7.5E-5            0.00          1.5E-4           0.00
        5.0E-8          5.0E-8            0.00          9.0E-8           0.00
        7.5E+3          7.5E+3           7.5E3          1.0E+4           3.E4
        5.0E+0          5.0E+0           5.0E0          7.5E+0           20.0
        5.0E-5          5.0E-5           5.E-5          1.0E-4          1.E-4
        1.0E-7          1.0E-7           1.E-7          2.0E-7          2.E-7
        15.0E3          15.0E3           15.E3          25.E+3         27.5E3
        3.0E+1          3.0E+1           3.0E1          5.0E+1          5.5E1
           1.0             2.0             5.0             10.            20.
           50.            100.
         .1E-3           .2E-3           .5E-3           1.E-3
           1.0             2.0             5.0             10.            20.
```

EXHIBIT A2. 2-4 (continued)

50.	100.				3430
10.	20.	50.	100.	200.	3440
500.	1.E3				3450
10.	1.E2	1.E3	1.E4	1.E5	3460
1.E6	1.E7	1.E8	1.E9	1.E10	3470
14.	.01	2.E4	25.	2.	3480
2.	8.75	2.3E-2	2.5E4	20.	3490
2.	2.	.21E-5	2.22	.66	3500
4.E6	0.	460.	1.	.039	3510
2.22	.66	2.E6	0.	350.	3520
1.	10.	.07	0.	100.	3530
0.	10.	2.	1.	3.33	3540
3.33	1250.	.125	1.E4	10.	3550
250.	.125	1.E4	10.	40.	3560

APPENDIX A2.3
OUTPUT DATA PROGRAM

FUNCTION

The function of the Output Data Program is to provide parametric plots as a function of transmission wavelength and information rate of the optimum values of the major system parameters and the corresponding system weight, power, fabrication cost and component cost burdens.

DESCRIPTION

Exhibit A2.3-1 is a flow chart of the Output Data Program.

The input information required for the program is the systems burdens data and the optimum value of the major system parameters, d_{TO}, d_{RO}, P_{TO}, θ_{RO}, as a function of information rate as determined by an optimization program.

Exhibit A2.3-2 contains a listing of the plots generated by the computer.

Exhibit A2.3-3 contains a listing of the Fortran Output Data Program.

OUTPUT DATA PROGRAM

START

READ AND PRINT SYSTEMS BURDENS DATA

READ AND PRINT OPTIMUM SYSTEM PARAMETERS

$d_{TO},\ d_{RO},\ P_{TO},\ \theta_{RO}$

COMPUTE, PLOT, AND PRINT OPTIMUM WEIGHT BURDENS

$$W_{d_T} = K_{d_T}(d_{TO})^{n_T} + W_{KT}$$

$$W_{d_R} = K_{d_R}(d_{RO})^{n_R} + W_{KR}$$

$$W_{QT} = W_{BT} + K_{W_{AT}} K_{d_T}(d_{TO})^{n_T}$$

$$W_{QR} = W_{BR} + K_{W_{AR}} K_{d_R}(d_{RO})^{n_R}$$

$$W_T = K_{W_T}(P_{TO})^{h_T} + W_{KP}$$

$$W_H = K_X \left(\frac{1 - k_e}{k_e}\right) P_{TO} + W_{KH}$$

$$W_M = K_M R_B + W_{KM}$$

$$W_D = K_D R_B + W_{KD}$$

$$W_{ST} = K_{W_{ST}} \left\{ K_{P_M} K_M R_B + K_{P_M} W_{K_M} + \frac{P_{TO}}{k_e} + K_{P_{QT}} \left[W_{BT} + K_{W_{AT}} K_{d_T}(d_{TO})^{n_T} \right] \right\} + W_{KE}$$

$$W_{SR} = K_{W_{SR}} \left\{ K_{P_D} K_D R_B + K_{P_D} W_{K_D} + K_{P_{QR}} \left[W_{BR} + K_{W_{AR}} K_{d_R}(d_{RO})^{n_R} \right] \right\} + W_{KF}$$

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$$W_A = W_{d_T} + W_{QT} + W_T + W_H + W_M + W_{ST}$$

$$W_B = W_{d_R} + W_{QR} + W_D + W_{SR}$$

COMPUTE, PLOT, AND PRINT OPTIMUM POWER BURDENS

$$P_{QT} = K_{P_{QT}}\left[W_{BT} + K_{W_{AT}} K_{d_T} (d_{TO})^{n_T}\right]$$

$$P_{QR} = K_{P_{QR}}\left[W_{BR} + K_{W_{AR}} K_{d_R} (d_{RO})^{n_R}\right]$$

$$P_{PT} = \frac{P_{TO}}{k_e} + P_{KT}$$

$$P_M = K_{P_M} K_M R_B + K_{P_M} W_{KM}$$

$$P_D = K_{P_D} K_D R_B + K_{P_D} W_{KD}$$

$$P_A = P_{QT} + P_{PT} + P_M$$

$$P_B = P_{QR} + P_D$$

COMPUTE, PLOT, AND PRINT OPTIMUM FABRICATION COST BURDENS

$$C_{\theta_T} = K_{\theta_T} (d_{TO})^{m_T} + C_{KT}$$

$$C_{\theta_R} = K_{\theta_R} (d_{RO})^{m_R} + C_{KR}$$

$$C_{NT} = C_{AT} + \frac{K_{AT}}{(\lambda)^{q_T}} (d_{TO})^{q_T}$$

$$C_{NR} = C_{AR} + K_{AR} (\theta_{RO})^{-q_R}$$

$$C_{FL} = K_{P_T} (P_{TO})^{g_T} + C_{KP}$$

$$C_H = K_H \left(\frac{1 - k_e}{k_e}\right) P_{TO} + C_{KH}$$

$$C_{FM} = K_{FM} R_B + C_{KM}$$

$$C_{FD} = K_{FD} R_B + C_{KD}$$

$$C_{FT} = K_{ST}\left\{K_{P_M} K_M R_B + K_{P_M} W_{KM} + \frac{P_{TO}}{k_e} + K_{P_{QT}}\left[W_{BT} + K_{W_{AT}} K_{d_T} (d_{TO})^{n_T}\right]\right\} + C_{KE}$$

$$C_{FR} = K_{SR}\left\{K_{P_D} K_D R_B + K_{P_D} W_{KD} + K_{P_{QR}}\left[W_{BR} + K_{W_{AR}} K_{d_R} (d_{RO})^{n_R}\right]\right\} + C_{KF}$$

$$C_{FA} = C_{\theta_T} + C_{NT} + C_{FL} + C_H + C_{FM} + C_{FT}$$

$$C_{FB} = C_{\theta_R} + C_{NR} + C_{FD} + C_{FR}$$

COMPUTE, PLOT, AND PRINT OPTIMUM SYSTEM COMPONENT COST BURDENS

$$C_{d_T} = C_{\theta_T} + K_S W_{d_T}$$

$$C_{d_R} = C_{\theta_R} + K_S W_{d_R}$$

$$C_{QT} = C_{AT} + K_S W_{QT}$$

$$C_{QR} = C_{AR} + K_S W_{QR}$$

$$C_{P_T} = C_{FL} + C_H + K_S W_T + K_S W_H$$

$$C_M = C_{FM} + K_S W_M$$

$$C_D = C_{FD} + K_S W_D$$

$$C_{ST} = C_{FT} + K_S W_{ST}$$

$$C_{SR} = C_{FR} + K_S W_{SR}$$

COMPUTE, PLOT, AND PRINT OPTIMUM SYSTEM COST BURDENS

$$K_{g_T} = K_{P_T}$$

$$K_{h_T} = K_S K_{W_T}$$

$$K_{i_T} = K_S \left\{ \frac{K_{W_{ST}}}{k_e} + K_X \left(\frac{1 - k_e}{k_e} \right) \right\} + \frac{K_{ST}}{k_e} + K_H \left(\frac{1 - k_e}{k_e} \right)$$

$$K_{m_T} = K_{\theta_T}$$

$$K_{n_T} = K_{d_T} \left\{ K_S \left[1 + K_{W_{AT}} \right] + K_{P_{QT}} K_{W_{AT}} \left[K_{ST} + K_S K_{W_{ST}} \right] \right\}$$

$$K_{q_T} = \frac{K_{AT}}{(\lambda)^{q_T}}$$

$$K_{m_R} = K_{\theta_R}$$

$$K_{n_R} = K_{d_R} \left\{ K_S \left[1 + K_{W_{AR}} \right] + K_{P_{QR}} K_{W_{AR}} \left[K_{SR} + K_S K_{W_{SR}} \right] \right\}$$

$$K_{q_R} = K_{AR}$$

$$C_{TO} = K_{q_T} (d_{TO})^{q_T} + K_{m_T} (d_{TO})^{m_T} + K_{n_T} (d_{TO})^{n_T}$$

$$C_{RO} = K_{m_R} (d_{RO})^{m_R} + K_{n_R} (d_{RO})^{n_R}$$

$$C_{QO} = K_{q_R} (\theta_{RO})^{-q_R}$$

$$C_{GO} = K_{g_T} (P_{TO})^{g_T} + K_{h_T} (P_{TO})^{h_T} + K_{i_T} (P_{TO})$$

$$C_V = C_{GO} + C_{TO} + C_{QO} + C_{RO}$$

$$C_S = C_V + C_{FA} + C_{FB}$$

$$C_A = C_{GO} + C_{TO} + C_{FA}$$

$$C_B = C_{QO} + C_{RO} + C_{FB}$$

EXHIBIT A2.3-2

OUTPUT DATA PROGRAM COMPUTER PLOTS

All plots versus transmission wavelength.

System Weight Burdens

W_{d_T} vs R_B

W_{d_R} vs R_B

W_{QT} vs R_B

W_{QR} vs R_B

W_T vs R_B

W_H vs R_B

W_M vs R_B

W_D vs R_B

W_{ST} vs R_B

W_{SR} vs R_B

W_A vs R_B

W_B vs R_B

System Power Burdens

P_{QT} vs R_B

P_{QR} vs R_B

P_{PT} vs R_B

P_M vs R_B

P_D vs R_B

P_A vs R_B

P_B vs R_B

System Fabrication Cost Burdens

C_{θ_T} vs R_B

C_{θ_R} vs R_B

C_{NT} vs R_B

C_{NR} vs R_B

C_{FL} vs R_B

C_H vs R_B

C_{FM} vs R_B

C_{FD} vs R_B

C_{FT} vs R_B

C_{FR} vs R_B

C_{FA} vs R_B

C_{FB} vs R_B

System Component Cost Burdens

C_{d_T} vs R_B

C_{d_R} vs R_B

C_{QT} vs R_B

C_{QR} vs R_B

C_{P_T} vs R_B

C_M vs R_B

C_D vs R_B

C_{ST} vs R_B

C_{SR} vs R_B

EXHIBIT A2. 3-2 (continued)

System Cost Variables

C_T vs R_B

C_R vs R_B

C_G vs R_B

C_Q vs R_B

C_V vs R_B

C_A vs R_B

C_B vs R_B

C_S vs R_B

EXHIBIT A2. 3-3

```
C OUTPUT     OPTIMIZATION METHODOLOGY;OUTPUT DATA PROGRAM

      SUBROUTINE OUTPUT(DTO,DRO,PTO,THERO,RB)
      REAL KTHT, KDT,  MT,  NT,KTHR, KDR,  MR,  NR, KAT,KWAT,KPOT, KAR
      REAL KWAR,KPQR, KPT, KWT,  KH,  KX,  KE, KFM,  KM, KPM, KFD,  KD
      REAL  KPD, KST,KWST, KSR,KWSR,  KS, KHT, KJT, KGT, KMT, KNT, KQT
      REAL  KMR, KNR, KQR,LAMBDA,LMBDI,K,KN
      COMMON/TRANT/ KTHT,KDT,CKT,WKT,MT,NT
      COMMON/RCANT/ KTHR,KDR,CKR,WKR,MR,NR
      COMMON/TACTS/ KAT,KWAT,KPOT,CAT,WBT,OT
      COMMON/RACTS/ KAR,KWAR,KPQR,CAR,WBR,QR
      COMMON/TRNSM/ KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      COMMON/EQMOD/ KFM,KM,KPM,CKM,WKM
      COMMON/EQDMD/ KFD,KD,KPD,CKD,WKD
      COMMON/TRNPS/ KST,KWST,CKE,WKE
      COMMON/RCVPS/KSR,KWSR,CKF,WKF
      COMMON/GENRL/ KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      COMMON/OUTPT/ KHT,KJT,KGT,KMT,KNT,KQT,KMR,KNR,KQR
      WRITE(6,1)RB,DTO,DRO,PTO,THERO
      WDT =KDT*DTO**MT + WKT
      WDR =KDR*DRO**NR + WKR
      WQT =WBT + KWAT*KDT *DTO**NT
      WQR =WBR + KWAR*KDR *DRO**NR
      WT = KWT*PTO**HT + WKP
      WH =  PTO*KX * (1.-KE)/KE + WKH
      WM = KM*RB + WKM
      WD = KD*RB  +  WKD
      WST = KWST*(KPM*KM*RB + KPM*WKM + PTO/KE  + KPQT* (WBT + KWAT*KDT
     *     *DTO**NT))  + WKE
      WSR = KWSR*(KPD*KD*RB + KPD*WKD  + KPQR*(WBR + KWAR*KDR*DRO**NR))
     *                                                          + WKF
      WA  = WDT + WQT + WT + WH + WM + WST
      WB  = WDR + WQR + WD + WSR
      WRITE (6,2) WDT,WDR,WQT,WQR,WT,WH,WM,WD,WST,WSR,WA,WB
      PQT = KPQT*(WBT + KWAT*KDT*DTO**NT)
      PQR = KPQR*(WBR + KWAR*KDR*DRO**NR)
      PPT =  PTO/KE + PKT
      PM  =  KPM*(KM*RB + WKM)
      PD  =  KPD*(KD*RB + WKD)
      PA  =  PQT + PPT + PM
      PB  = PQR + PD
      WRITE(6,3) PQT,PQR,PPT,PM,PD,PA,PB
      CTHT =  KTHT * DTO**MT + CKT
      CTHR =  KTHR * DRO**MR + CKR
      CNT  = CAT + KAT*(DTO/LAMBDA)**QT
      CNR  = CAR + KAR*THERO**(-QR)
      CFL  = KPT*PTO**GT +CKP
      CH = PTO*KH*(1.-KE)/KE + CKH
      CFM = KFM*RB + CKM
      CFD = KFD*RB + CKD
      CFT = KST*(KPM*(KM*RB + WKM) + PTO/KE  + KPQT*(WBT +KWAT*DTO**NT))
     *                                                           + CKE
      CFR = KSR*(KPD*(KD*RB + WKD) + KPQR*(WBR + KWAR*KDR*DRO**NR))+ CKF
      CFA = CTHT + CNT + CFL + CH + CFM + CFT
      CFB = CTHR + CNR + CFD + CFR
      WRITE(6,4) CTHT,CTHR,CNT,CNR,CFL,CH,CFM,CFD,CFT,CFR,CFA,CFB
```

```
      CDT  = CTHT + KS*WDT
      CDR  =         CTHR + KS*WDR
      CQT  = CAT + KS*WQT
      CQR  = CAR + KS*WQR
      CPT  = CFL + CH +KS*(WT + WH)
      CM  = CFM + KS*WM
      CD  = CFD + KS*WD
      CST  = CFT + KS*WST
      CSR  = CFR + KS*WSR
      WRITE(6,5) CDT,CDR,CQT,CQR,CPT,CM,CD,CST,CSR
      KHT  = KS*KWT
      KJT  =(KS*KWST + KST)/KF  +(KS*KX + KH )*(1.-KF)/KF
      KGT  = KPT
      KMT  = KTHT
      KNT  = KDT*(KS*(1. + KWAT) + KPQT*KWAT*(KST + KS*KWST))
      KQT  = KAT/LAMBDA**QT
      KMR  = KTHR
      KNR  = KDR*(KS*(1. + KWAR) + KPQR*KWAR*(KSR + KS*KWSR))
      KQR  = KAR
      CTO  = KQT*DTO**QT +KMT*DTO**MT + KNT*DTO**NT
      CRO  = KMR*DRO**MR + KNR*DRO**NR
      CQO  = KQR/THERO**QR
      CGO  = KGT*PTO**GT + KHT*PTO**HT  +KJT*PTO
      CV  = CGO +CTO + CQO + CRO
      CS  = CV + CFA +CFB
      CA  = CGO +CTO + CFA
      CB  = CQO + CRO +CFB
      WRITE(6,6) CTO,CRO,CQO,CGO,CV,CS,CA,CB
    1 FORMAT(35H OPTIMUM SYSTEM PARAMETERS    RB = ,E12.5,9H   DTO = ,
     *E12.5,9H   DRO   ,E12.5,9H   PTO = ,E12.5,10H  THERO = ,E12.5//)
    2 FORMAT(     23H OPTIMUM WEIGHT BURDENS, 5H  WDT,E15.6,5H  WDR,E15.6
     *,5H  WQT,E15.6,5H  WQR,E15.6,5H   WT,E15.6/23X,        5H   WH,
     *E15.6,5H   WM,E15.6,5H   WD,E15.6,5H  WST,E15.6,5H  WSR,E15.6/23X,
     * 5H   WA,E15.6,5H   WB,E15.6//)
    3 FORMAT(     23H OPTIMUM POWER BURDENS , 5H  PQT,E15.6,5H  PQR,E15.6
     *,5H  PPT,E15.6,5H   PM,E15.6,5H   PD,E15.6/23X,5H   PA,E15.6,5H
     *PB,E15.6//)
    4 FORMAT(33H OPTIMUM FABRICATION COST BURDENS,10X,5H CTHT,E15.6,5H C
     *THR,E15.6,5H  CNT,E15.6,5H  CNR,E15.6/23X,5H  CFL,E15.6,5H   CH,
     *E15.6,5H  CFM,E15.6,5H  CFD,E15.6,5H  CFT,E15.6/5H  CFR,E15.6,5H
     *CFA,E15.6,5H  CFB,E15.6//)
    5 FORMAT(38H OPTIMUM SYSTEM COMPONENT COST BURDENS,5X,5H  CDT,E15.6,
     *5H  CDR,E15.6,5H  CQT,E15.6,5H  CQR,E15.6/23X,5H  CPT,E15.6,5H   C
     *M,E15.6,5H   CD,E15.6,5H  CST,E15.6,5H  CSR,E15.6//)
    6 FORMAT(28H OPTIMUM SYSTEM COST BURDENS,15X,5H  CTO,E15.6,5H  CRO,
     *E15.6,5H  CQO,E15.6,5H  CGO,E15.6/23X,5H   CV,E15.6,5H   CS,E15.6,
     *5H   CA,E15.6,5H   CB,E15.6///)
      RETURN
      END
```

APPENDIX A2.5

THERMAL NOISE LIMITED DIRECT DETECTION OPTICAL RECEIVER OPTIMIZATION PROGRAM (TOP) WITHOUT COMPONENT STOPS

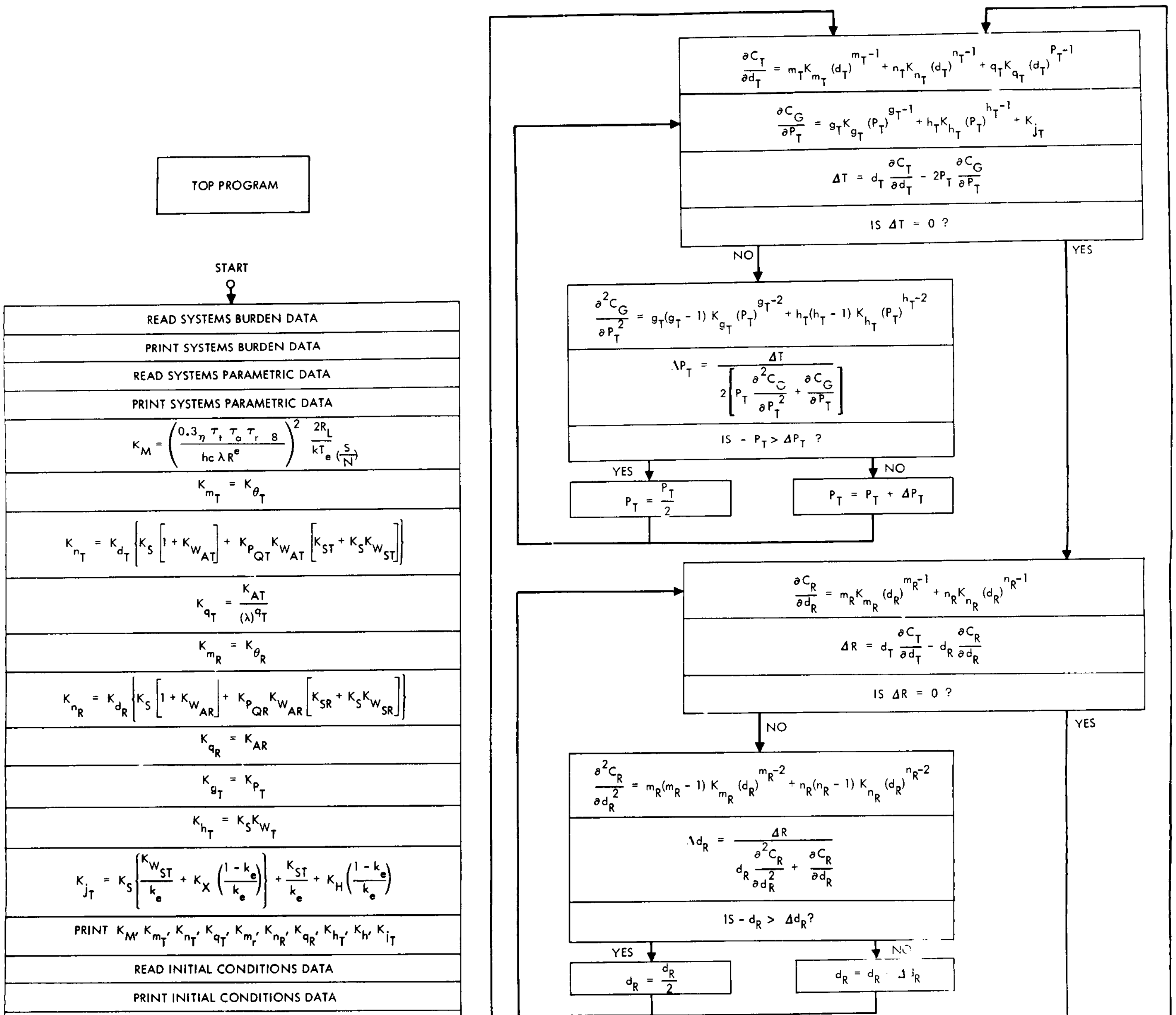
FUNCTION

The function of the TOP program is to determine the optimum values of the major system parameters as a function of information rate for a thermal noise limited direct detection optical receiver.

DESCRIPTION

Exhibit A2.5-1 is a detailed flow chart of the TOP optimization program. The input information required for the TOP program is the systems burden data, the system parametric data, and the initial conditions data. Exhibit A2.5-2 contains a listing of the Fortran IV TOP program.

A2.5-2



TOP PROGRAM
START
READ SYSTEMS BURDEN DATA
PRINT SYSTEMS BURDEN DATA
READ SYSTEMS PARAMETRIC DATA
PRINT SYSTEMS PARAMETRIC DATA
$K_M = \left(\frac{0.3 \eta \tau_t \tau_a \tau_r 8}{hc \lambda R^e}\right)^2 \frac{2R_L}{kT_e (\frac{S}{N})}$
$K_{m_T} = K_{\theta_T}$
$K_{n_T} = K_{d_T}\left\{K_S\left[1 + K_{W_{AT}}\right] + K_{P_{QT}} K_{W_{AT}}\left[K_{ST} + K_S K_{W_{ST}}\right]\right\}$
$K_{q_T} = \frac{K_{AT}}{(\lambda)^{q_T}}$
$K_{m_R} = K_{\theta_R}$
$K_{n_R} = K_{d_R}\left\{K_S\left[1 + K_{W_{AR}}\right] + K_{P_{QR}} K_{W_{AR}}\left[K_{SR} + K_S K_{W_{SR}}\right]\right\}$
$K_{q_R} = K_{AR}$
$K_{g_T} = K_{P_T}$
$K_{h_T} = K_S K_{W_T}$
$K_{j_T} = K_S\left\{\frac{K_{W_{ST}}}{k_e} + K_X\left(\frac{1 - k_e}{k_e}\right)\right\} + \frac{K_{ST}}{k_e} + K_H\left(\frac{1 - k_e}{k_e}\right)$
PRINT $K_M, K_{m_T}, K_{n_T}, K_{q_T}, K_{m_r}, K_{n_R}, K_{q_R}, K_{h_T}, K_h, K_{i_T}$
READ INITIAL CONDITIONS DATA
PRINT INITIAL CONDITIONS DATA
$\frac{\partial C_T}{\partial d_T} = m_T K_{m_T} (d_T)^{m_T - 1} + n_T K_{n_T} (d_T)^{n_T - 1} + q_T K_{q_T} (d_T)^{P_T - 1}$
$\frac{\partial C_G}{\partial P_T} = g_T K_{g_T} (P_T)^{g_T - 1} + h_T K_{h_T} (P_T)^{h_T - 1} + K_{j_T}$
$\Delta T = d_T \frac{\partial C_T}{\partial d_T} - 2P_T \frac{\partial C_G}{\partial P_T}$
IS $\Delta T = 0$?
NO
YES
$\frac{\partial^2 C_G}{\partial P_T^2} = g_T(g_T - 1) K_{g_T} (P_T)^{g_T - 2} + h_T(h_T - 1) K_{h_T} (P_T)^{h_T - 2}$
$\Delta P_T = \frac{\Delta T}{2\left[P_T \frac{\partial^2 C_G}{\partial P_T^2} + \frac{\partial C_G}{\partial P_T}\right]}$
IS $- P_T > \Delta P_T$?
YES
NO
$P_T = \frac{P_T}{2}$
$P_T = P_T + \Delta P_T$
$\frac{\partial C_R}{\partial d_R} = m_R K_{m_R} (d_R)^{m_R - 1} + n_R K_{n_R} (d_R)^{n_R - 1}$
$\Delta R = d_T \frac{\partial C_T}{\partial d_T} - d_R \frac{\partial C_R}{\partial d_R}$
IS $\Delta R = 0$?
NO
YES
$\frac{\partial^2 C_R}{\partial d_R^2} = m_R(m_R - 1) K_{m_R} (d_R)^{m_R - 2} + n_R(n_R - 1) K_{n_R} (d_R)^{n_R - 2}$
$\Delta d_R = \frac{\Delta R}{d_R \frac{\partial^2 C_R}{\partial d_R^2} + \frac{\partial C_R}{\partial d_R}}$
IS $- d_R > \Delta d_R$?
YES
NO
$d_R = \frac{d_R}{2}$
$d_R = d_R + \Delta d_R$

$$d_R = d_{RI}$$
$$P_T = P_{TI}$$
$$\theta_R = \theta_{RM}$$
$$C_V = C_{VI}$$

$$C_T = K_{m_T}(d_T)^{m_T} + K_{n_T}(d_T)^{n_T} + K_{q_T}(d_T)^{q_T}$$

$$C_R = K_{m_R}(d_R)^{m_R} + K_{n_R}(d_R)^{n_R}$$

$$C_G = K_{g_T}(P_T)^{g_T} + K_{h_T}(P_T)^{h_T} + K_{g_T} P_T$$

$$C_Q = K_{q_R}\left(\theta_{RM}\right)^{-q_R}$$

$$C_{VA} = C_T + C_R + C_G + C_Q$$

IS $C_{VA} = C_V$?

NO

$$\frac{\partial C_T}{\partial d_T} = m_T K_{m_T}(d_T)^{m_T-1} + n_T K_{n_T}(d_T)^{n_T-1} + q_T K_{q_T}(d_T)^{q_T-1}$$

$$\frac{\partial C_R}{\partial d_R} = m_R K_{m_R}(d_R)^{m_R-1} + n_R K_{n_R}(d_R)^{n_R-1}$$

$$\frac{\partial C_G}{\partial P_T} = g_T K_{g_T}(P_T)^{g_T-1} + h_T K_{h_T}(P_T)^{h_T-1} + K_{j_T}$$

$$\frac{\partial^2 C_T}{\partial d_T^2} = m_T(m_T-1) K_{m_T}(d_T)^{m_T-2} + n_T(n_T-1) K_{n_T}(d_T)^{n_T-2} + q_T(q_T-1) K_{q_T}(d_T)^{q_T-2}$$

$$\frac{\partial^2 C_R}{\partial d_R^2} = m_R(m_R-1) K_{m_R}(d_R)^{m_R-2} + n_R(n_R-1) K_{n_R}(d_R)^{n_R-2}$$

$$\frac{\partial^2 C_G}{\partial P_T^2} = g_T(g_T-1) K_{q_T}(P_T)^{g_T-2}, + h_T(h_T-1) K_{h_T}(P_T)^{h_T-2}$$

$$\frac{\partial P_T}{\partial d_T} = \frac{d_T \frac{\partial^2 C_T}{\partial d_T^2} + \frac{\partial C_T}{\partial d_T}}{2\frac{\partial C_G}{\partial P_T} + 2P_T \frac{\partial^2 C_G}{\partial P_T^2}}$$

$$\frac{\partial d_R}{\partial d_T} = \frac{d_T \frac{\partial^2 C_T}{\partial d_T^2} + \frac{\partial C_T}{\partial d_T}}{\frac{\partial C_R}{\partial d_R} + d_R \frac{\partial^2 C_R}{\partial d_R^2}}$$

$$\delta d_T = \frac{C_V - C_{VA}}{\frac{\partial C_T}{\partial d_T} + \frac{\partial C_R}{\partial d_R} \cdot \frac{\partial d_R}{\partial d_T} + \frac{\partial C_G}{\partial P_T}\frac{\partial P_T}{\partial d_T}}$$

$$d_T = d_T + \delta d_T$$

YES

$$d_{RO} = d_T$$
$$P_{TO} = P_T$$
$$d_{TO} = d_R$$
$$\theta_{RO} = \theta_{RM}$$

$$R_B = K_M \; d_{TO}^4 \; d_{RO}^4 \; P_{TO}^2$$

EXIT

EXHIBIT A2. 5-2

```
CTOP          OPTIMIZATION METHODOLOGY TOP PROGRAM

      REAL KTHT, KDT,  MT,  NT,KTHR, KDR,  MR,  NR, KAT,KWAT,KPQT, KAR
      REAL KWAR,KPQR, KPT, KWT,  KH,  KX,  KE, KFM,  KM, KPM, KFD,  KD
      REAL  KPD, KST,KWST, KSR,KWSR,  KS, KHT, KJT, KGT, KMT, KNT, KQT
      REAL  KMR, KNR, KQR,LAMBDA,LMBDI,K,KN                            0
      COMMON/TRANT/ KTHT,KDT,CKT,WKT,MT,NT
      COMMON/RCANT/ KTHR,KDR,CKR,WKR,MR,NR
      COMMON/TACTS/ KAT,KWAT,KPQT,CAT,WBT,QT
      COMMON/RACTS/ KAR,KWAR,KPQR,CAR,WBR,QR
      COMMON/TRNSM/ KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      COMMON/EQMOD/ KFM,KM,KPM,CKM,WKM
      COMMON/EQDMD/ KFD,KD,KPD,CKD,WKD
      COMMON/TRNPS/ KST,KWST,CKE,WKE
      COMMON/RCVPS/KSR,KWSR,CKF,WKF
      COMMON/GENRL/ KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      COMMON/OUTPT/ KHT,KJT,KGT,KMT,KNT,KQT,KMR,KNR,KQR
      READ(5,1100) KTHT,KDT,CKT,WKT,MT,NT
      WRITE(6,1200)KTHT,KDT,CKT,WKT,MT,NT
      READ(5,1100) KTHR,KDR,CKR,WKR,MR,NR
      WRITE(6,1201)KTHR,KDR,CKR,WKR,MR,NR
      READ(5,1100) KAT,KWAT,KPQT,CAT,WBT,QT
      WRITE(6,1202)KAT,KWAT,KPQT,CAT,WBT,QT
      READ(5,1100) KAR,KWAR,KPQR,CAR,WBR,QR
      WRITE(6,1203)KAR,KWAR,KPQR,CAR,WBR,QR
      READ(5,1100) KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      WRITE(6,1204)KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      READ(5,1100) KFM,KM,KPM,CKM,WKM
      WRITE(6,1205)KFM,KM,KPM,CKM,WKM
      READ(5,1100) KFD,KD,KPD,CKD,WKD
      WRITE(6,1206)KFD,KD,KPD,CKD,WKD
      READ (5,1100) KST,KWST,CKE,WKE
      WRITE(6,1207) KST,KWST,CKE,WKE
      READ(5,1100) KSR,KWSR,CKF,WKF
      WRITE(6,1208)KSR,KWSR,CKF,WKF
      WRITE(6,1210)H,C,Q,SMK,TE,RL
      READ(5,1100) H,C,Q,SMK,TE,RL
      READ(5,1100) KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      WRITE(6,1209)KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      KM = (.3*ETA*TAUT*TAUA*TAUR*Q/((H*R**2)*C*LAMBDA))**2
     *                                        *(2.*RL)/(SMK*TE*SN)
      KMT = KTHT
      KNT = KDT*(KS*(1.+KWAT)+ KPQT*KWAT*(KST+KS*KWST))
      KQT = KAT/LAMBDA**QT
      KMR = KTHR
      KNR = KDR*(KS*(1.+ KWAR) +KPQR*KWAR*(KSR + KS*KWSR))
      KGT = KPT
      KHT = KS*KWT
      KJT = KS*(KWST/KE + KX*(1.-KE)/KE) + KST/KE + KH*(1.-KE)/KE
      KQR = KAR
      WRITE (6,2000)KN,K,KMT,KNT,KQT,KMR,KNR,KQR,KGT,KHT,KJT
      READ (5,1100) DTI,DRI,PTI,THERI,CVI,CVMIN
      CV = CVI
      DELCV = CV/10.
      DT = DTI
      PT = PTI
```

EXHIBIT A2. 5-2 (continued)

```
      DR = DRI
      THER = THERI
      WRITE (6,2001) THER,DT,DR,PT,CV
    8 PCTPDT =(MT*KMT*DT**MT + NT*KNT*DT**NT +QT*KQT*DT**QT)/DT
   10 PCGPPT =(GT*KGT*PT**GT + HT*KHT*PT**HT)/PT + KJT
      F1 = DT*PCTPDT
      F2 =  2.*PT * PCGPPT
      T  = F1 - F2
      IF((F1/F2) .GT. .999995 .AND. (F1/F2) .LT. 1.000005 ) GO TO 60
      PCGPT2 = (GT*(GT-1.)*KGT*PT**GT +HT*(HT-1.)*KHT*PT**HT)/PT**2
      DELPT  = T/(2.*(PT*PCGPT2 +PCGPPT))
      XXX = PT + DELPT
      IF(XXX .LT. 0.) XXX = PT/2.
      PT = XXX
      GO TO 10
   60 CONTINUE
   80 PCRPDR = (MR*KMR*DR**MR +    NR*KNR*DR**NR)/DR
      F1 =  DT*PCTPDT
      F2 = DR*PCRPDR
      W = F1 - F2
      IF((F1/F2) .GT. .999995 .AND. (F1/F2) .LT. 1.000005 )GO TO 100
      PCRDR2 =(MR*(MR-1.)*KMR*DR**MR +NR*(NR-1.)*KNR*DR**NR)/DR**2
      DELDR = W/(DR*PCRDR2 + PCRPDR)
      XXX= DR + DELDR
      IF( XXX .LT. 0. ) XXX = DR/2.
      DR = XXX
      GO TO 80
  100 CT = KMT*DT**MT +KNT*DT**NT +KQT*DT**QT
      CR = KMR*DR**MR +KNR*DR**NR
      CG =  KGT*PT**GT  + KHT*PT**HT + KJT*PT
      CQ = KQR*THER**(-QR)
      CVA = CT+ CR + CG + CQ
      IF((CV/CVA) .GT. .99995 .AND. (CV/CVA) .LT. 1.00005 ) GO TO 280
      PCTPDT = (MT*KMT*DT**MT + NT*KNT*DT**NT + QT*KQT*DT**QT)/DT
      PCRPDR = (MR*KMR*DR**MR + NR*KNR*DR**NR )/DR
      PCGPPT = (GT*KGT*PT**GT + HT*KHT*PT**HT )/PT + KJT
      PCTDT2 = (MT*KMT*(MT-1.)*DT**MT  + NT*(NT-1.)*KNT*DT**NT + QT*
     *                                (QT-1.)*KQT*DT**QT)/DT**2
      PCRDR2 =(MR*(MR-1.)*KMR*DR**MR + NR*(NR-1.)*KNR*DR**NR)/DR**2
      PCGPT2 =(GT*(GT-1.)*KGT*PT**GT + HT*(HT-1.)*KHT*PT**HT)/PT**2
      PPTPDT =(DT*PCTDT2 +PCTPDT)/(2.*PCGPPT+ 2.*PT*PCGPT2)
      PDRPDT = (DT*PCTDT2 + PCTPDT)/(PCRPDR + DR*PCRDR2)
      DELDT  = (CV-CVA)/( PCTPDT +PCRPDR*PDRPDT +PCGPPT*PPTPDT)
      XXX = DELDT +DT
      IF( XXX .LT. 0. ) XXX = DT/2.
      DT = XXX
      GO TO 8
  280 DTO = DT
      PTO = PT
      DRO = DR
      THERO = THER
      RB = KN*DTO**2 *DRO**2 *PTO
      CALL OUTPUT(DTO,DRO,PTO,THERO,RB)
      IF(CV .LE. CVMIN) GO TO 370
      IF(CV .EQ. DELCV) DELCV = DELCV/10.
      CV = CV - DELCV
      GO TO 8
```

EXHIBIT A2. 5-2 (continued)

```
 370 STOP
1100 FORMAT (6E12.5)
1200 FORMAT (15H1 TRANSMITTER   ,5H KTHT,E13.5,5H KDT ,E13.5,5H CKT ,E13
    *.5,5H WKT ,E13.5,5H MT   ,E13.5,5H NT   ,E13.5/15H  ANTENNA        //)
1201 FORMAT (15H  RECEIVER      ,5H KTHR,E13.5,5H KDR ,E13.5,5H CKR ,E13
    *.5,5H WKR ,E13.5,5H MR   ,E13.5,5H NR   ,E13.5/15H  ANTENNA        //)
1202 FORMAT (15H  TRANSMITTER   ,5H KAT ,E13.5,5H KWAT,E13.5,5H KPQT,E13
    *.5,5H CAT ,E13.5,5H WBT ,E13.5,5H QT   ,E13.5/15H  ACQUISITION   /
    *                                             15H  AND TRACK     /
    *                                             15H  SYSTEM         //)
1203 FORMAT (15H  RECEIVER      ,5H KAR ,E13.5,5H KWAR,E13.5,5H KPQR,E13
    *.5,5H CAR ,E13.5,5H WBR ,E13.5,5H QR   ,E13.5/15H  ACQUISITION   /
    *                                             15H  AND TRACK
    *                                            /15H  SYSTEM         //)
1204 FORMAT (15H  TRANSMITTER   ,5H KPT ,E13.5,5H KWT ,E13.5,5H KH  ,E13
    *.5,5H KX   ,E13.5,5H KE   ,F13.5,5H CKP ,E13.5/15X,5H CKH ,E13.5,5H
    *WKP ,E13.5,5H WKH ,E13.5,5H PKT ,E13.5,5H GT   ,E13.5,5H HT   ,E13.5
    *                                                                   //)
1205 FORMAT (15H  MODULATION    ,5H KFM ,E13.5,5H KM   ,E13.5,5H KPM ,E13
    *.5,5H CKM ,E13.5,5H WKM ,E13.5/15H  EQUIPMENT      //)
1206 FORMAT (15H  DEMODULATION ,5H KFD ,E13.5,5H KD   ,E13.5,5H KPD ,E13
    *.5,5H CKD ,E13.5,5H WKD ,E13.5/15H  EQUIPMENT      //)
1207 FORMAT (15H  TRANSMITTER   ,5H KST ,E13.5,5H KWST,E13.5,5H CKE ,E13
    *.5,5H WKE ,E13.5/15H  POWER SUPPLY //)
1208 FORMAT (15H  RECEIVER      ,5H KSR ,E13.5,5H KWSR,E13.5,5H CKF ,E13
    *.5,5H WKF ,E13.5/15H  POWER SUPPLY //)
1209 FORMAT ( 7H  KS = ,E13.5,11H  LAMBDA = ,F13.5,13H  LAMBDA I = ,E13
    *.5,6H  R = ,E13.5,10H  TAU T = ,F13.5//10H  TAU R = ,E13.5,10H  TA
    *U A = ,E13.5, 8H  ETA = ,E13.5,11H   (S/N) = ,E13.5,7H  QB = ,E13.
    *5/2H1 )
1210 FORMAT(7H    H = ,E13.5,7H    C = ,E13.5,7H    Q = ,E13.5,7H SMK = ,
    *E13.5,7H  TE = ,E13.5,7H  RL = ,E13.5//)
2000 FORMAT( 7H1 KN = ,E18.8,7H   K = ,E18.8,7H KMT = ,E18.8,7H KNT = ,
    * E18.8,7H KQT = ,E18.8/ 7H KMR = ,E18.8,7H KNR = ,E18.8,7H KQR = ,
    * E18.8,7H KGT = ,E18.8, 7H KHT = ,E18.8/7H KJT = ,E18.8///)
2001 FORMAT(53X,23HINITIAL CONDITIONS DATA//11H THETA-R = ,E12.5,
    * 6H DT = ,E12.5,6H DR = ,E12.5,6H PT = ,E12.5,6H CV = ,E12.5// )
     END
```

APPENDIX A2.6

HETERODYNE DETECTION OPTICAL RECEIVER OPTIMIZATION PROGRAM WITHOUT COMPONENT STOPS (HOP)

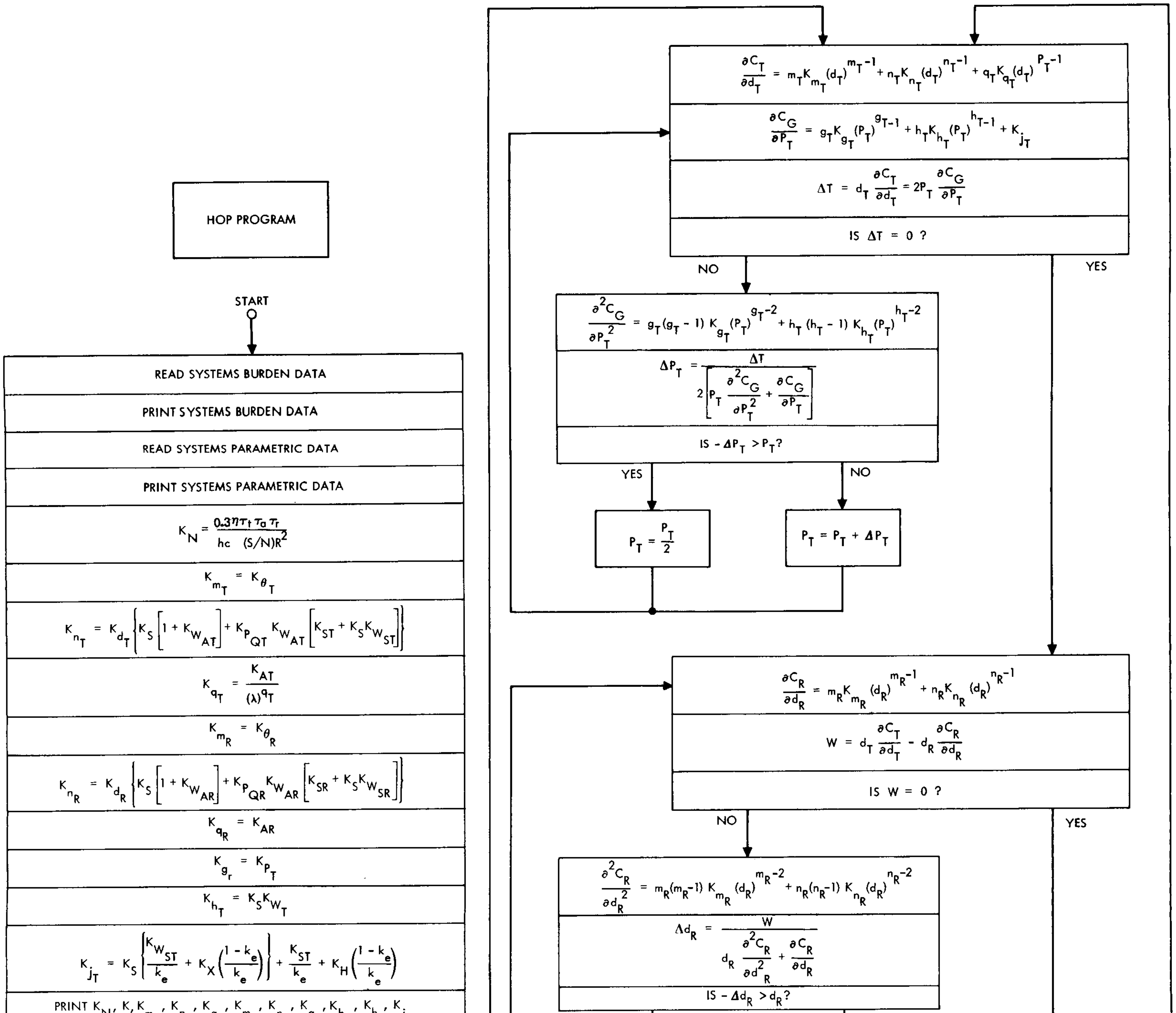
FUNCTION

The function of the HOP program is to determine the optimum values of the major system parameters as a function of information rate for a heterodyne detection optical receiver.

DESCRIPTION

Exhibit A2.6-1 is a detailed flow chart of the HOP optimization program. The input information required for the HOP program is the systems burden data, the system parametric data, and the initial conditions data. Exhibit A2.6-2 contains a listing of the Fortran IV HOP program.

HOP PROGRAM


START
READ SYSTEMS BURDEN DATA
PRINT SYSTEMS BURDEN DATA
READ SYSTEMS PARAMETRIC DATA
PRINT SYSTEMS PARAMETRIC DATA
$K_N = \frac{0.3\eta\tau_t\tau_a\tau_r}{hc\ (S/N)R^2}$
$K_{m_T} = K_{\theta_T}$
$K_{n_T} = K_{d_T}\left\{K_S\left[1+K_{W_{AT}}\right]+K_{P_{QT}}K_{W_{AT}}\left[K_{ST}+K_SK_{W_{ST}}\right]\right\}$
$K_{q_T} = \frac{K_{AT}}{(\lambda)^{q_T}}$
$K_{m_R} = K_{\theta_R}$
$K_{n_R} = K_{d_R}\left\{K_S\left[1+K_{W_{AR}}\right]+K_{P_{QR}}K_{W_{AR}}\left[K_{SR}+K_SK_{W_{SR}}\right]\right\}$
$K_{q_R} = K_{AR}$
$K_{g_r} = K_{P_T}$
$K_{h_T} = K_SK_{W_T}$
$K_{j_T} = K_S\left\{\frac{K_{W_{ST}}}{k_e}+K_X\left(\frac{1-k_e}{k_e}\right)\right\}+\frac{K_{ST}}{k_e}+K_H\left(\frac{1-k_e}{k_e}\right)$
PRINT
$\frac{\partial C_T}{\partial d_T} = m_TK_{m_T}(d_T)^{m_T-1}+n_TK_{n_T}(d_T)^{n_T-1}+q_TK_{q_T}(d_T)^{P_T-1}$
$\frac{\partial C_G}{\partial P_T} = g_TK_{g_T}(P_T)^{g_T-1}+h_TK_{h_T}(P_T)^{h_T-1}+K_{j_T}$
$\Delta T = d_T\frac{\partial C_T}{\partial d_T} = 2P_T\frac{\partial C_G}{\partial P_T}$
IS $\Delta T = 0$?
NO
YES
$\frac{\partial^2 C_G}{\partial P_T^2} = g_T(g_T-1)K_{g_T}(P_T)^{g_T-2}+h_T(h_T-1)K_{h_T}(P_T)^{h_T-2}$
$\Delta P_T = \frac{\Delta T}{2\left[P_T\frac{\partial^2 C_G}{\partial P_T^2}+\frac{\partial C_G}{\partial P_T}\right]}$
IS $-\Delta P_T > P_T$?
YES
NO
$P_T = \frac{P_T}{2}$
$P_T = P_T + \Delta P_T$
$\frac{\partial C_R}{\partial d_R} = m_RK_{m_R}(d_R)^{m_R-1}+n_RK_{n_R}(d_R)^{n_R-1}$
$W = d_T\frac{\partial C_T}{\partial d_T} - d_R\frac{\partial C_R}{\partial d_R}$
IS $W = 0$?
NO
YES
$\frac{\partial^2 C_R}{\partial d_R^2} = m_R(m_R-1)K_{m_R}(d_R)^{m_R-2}+n_R(n_R-1)K_{n_R}(d_R)^{n_R-2}$
$\Delta d_R = \frac{W}{d_R\frac{\partial^2 C_R}{\partial d_R^2}+\frac{\partial C_R}{\partial d_R}}$
IS $-\Delta d_R > d_R$?

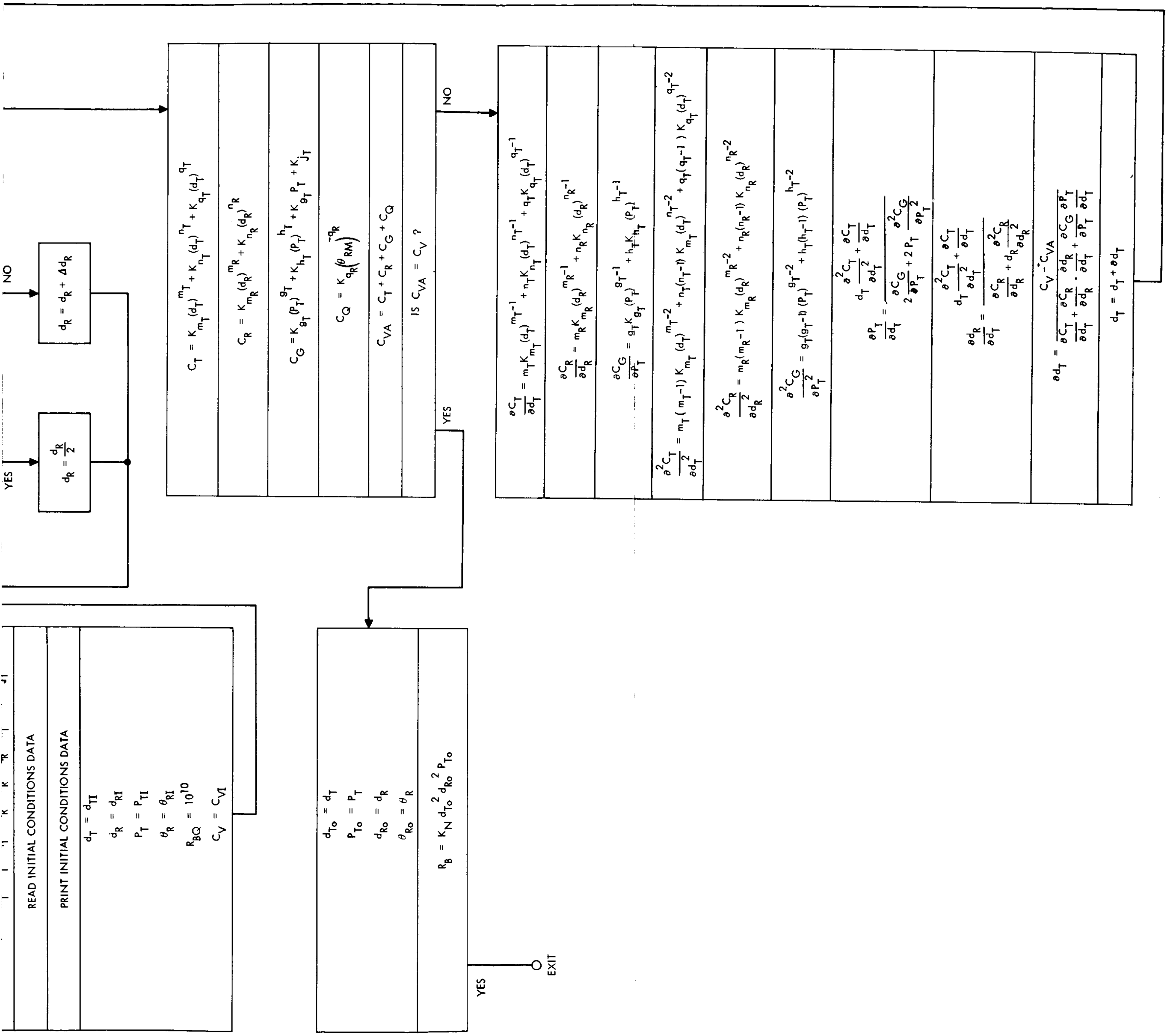

NO
$d_R = d_R + \Delta d_R$
YES
$d_R = \frac{d_R}{2}$
$C_T = K_{m_T}(d_T)^{m_T} + K_{n_T}(d_T)^{n_T} + K_{q_T}(d_T)^{q_T}$
$C_R = K_{m_R}(d_R)^{m_R} + K_{n_R}(d_R)^{n_R}$
$C_G = K_{g_T}(P_T)^{g_T} + K_{h_T}(P_T)^{h_T} + K_{g_T}P_T + K_{j_T}$
$C_Q = K_{q_R}\left(\theta_{RM}\right)^{-q_R}$
$C_{VA} = C_T + C_R + C_G + C_Q$
IS $C_{VA} = C_V$?
NO
YES
$\frac{\partial C_T}{\partial d_T} = m_T K_{m_T}(d_T)^{m_T-1} + n_T K_{n_T}(d_T)^{n_T-1} + q_T K_{q_T}(d_T)^{q_T-1}$
$\frac{\partial C_R}{\partial d_R} = m_R K_{m_R}(d_R)^{m_R-1} + n_R K_{n_R}(d_R)^{n_R-1}$
$\frac{\partial C_G}{\partial P_T} = g_T K_{g_T}(P_T)^{g_T-1} + h_T K_{h_T}(P_T)^{h_T-1}$
$\frac{\partial^2 C_T}{\partial d_T^2} = m_T(m_T-1) K_{m_T}(d_T)^{m_T-2} + n_T(n_T-1) K_{m_T}(d_T)^{n_T-2} + q_T(q_T-1) K_{q_T}(d_T)^{q_T-2}$
$\frac{\partial^2 C_R}{\partial d_R^2} = m_R(m_R-1) K_{m_R}(d_R)^{m_R-2} + n_R(n_R-1) K_{n_R}(d_R)^{n_R-2}$
$\frac{\partial^2 C_G}{\partial P_T^2} = g_T(g_T-1)(P_T)^{g_T-2} + h_T(h_T-1)(P_T)^{h_T-2}$
$\frac{\partial P_T}{\partial d_T} = \frac{d_T \frac{\partial^2 C_T}{\partial d_T^2} + \frac{\partial C_T}{\partial d_T}}{2\frac{\partial C_G}{\partial P_T} + 2P_T \frac{\partial^2 C_G}{\partial P_T^2}}$
$\frac{\partial d_R}{\partial d_T} = \frac{d_T \frac{\partial^2 C_T}{\partial d_T^2} + \frac{\partial C_T}{\partial d_T}}{\frac{\partial C_R}{\partial d_R} + d_R \frac{\partial^2 C_R}{\partial d_R^2}}$
$\partial d_T = \frac{C_V - C_{VA}}{\frac{\partial C_T}{\partial d_T} + \frac{\partial C_R}{\partial d_R} \cdot \frac{\partial d_R}{\partial d_T} + \frac{\partial C_G}{\partial P_T} \cdot \frac{\partial P_T}{\partial d_T}}$
$d_T = d_T + \partial d_T$
READ INITIAL CONDITIONS DATA
PRINT INITIAL CONDITIONS DATA
$d_T = d_{TI}$
$d_R = d_{RI}$
$P_T = P_{TI}$
$\theta_R = \theta_{RI}$
$R_{BQ} = 10^{10}$
$C_V = C_{VI}$
$d_{To} = d_T$
$P_{To} = P_T$
$d_{Ro} = d_R$
$\theta_{Ro} = \theta_R$
$R_B = K_N d_{To}^2 d_{Ro}^2 P_{To}$
YES
EXIT

EXHIBIT A2. 6-2

CHOP   OPTIMIZATION METHODOLOGY HOP PROGRAM

```
      REAL KTHT, KDT,  MT,  NT,KTHR, KDR,  MR,  NR, KAT,KWAT,KPQT, KAR
      REAL KWAR,KPQR, KPT, KWT,  KH,  KX,  KE, KFM,  KM, KPM, KFD,  KD
      REAL  KPD, KST,KWST, KSR,KWSR,  KS, KHT, KJT, KGT, KMT, KNT, KQT
      REAL  KMR, KNR, KQR,LAMBDA,LMBDI,K,KN
      COMMON/TRANT/ KTHT,KDT,CKT,WKT,MT,NT
      COMMON/RCANT/ KTHR,KDR,CKR,WKR,MR,NR
      COMMON/TACTS/ KAT,KWAT,KPQT,CAT,WBT,QT
      COMMON/RACTS/ KAR,KWAR,KPQR,CAR,WBR,QR
      COMMON/TRNSM/ KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      COMMON/EQMOD/ KFM,KM,KPM,CKM,WKM
      COMMON/EQDMD/ KFD,KD,KPD,CKD,WKD
      COMMON/TRNPS/ KST,KWST,CKE,WKE
      COMMON/RCVPS/KSR,KWSR,CKF,WKF
      COMMON/GENRL/ KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      COMMON/OUTPT/ KHT,KJT,KGT,KMT,KNT,KQT,KMR,KNR,KQR
      READ(5,1100) KTHT,KDT,CKT,WKT,MT,NT
      WRITE(6,1200)KTHT,KDT,CKT,WKT,MT,NT
      READ(5,1100) KTHR,KDR,CKR,WKR,MR,NR
      WRITE(6,1201)KTHR,KDR,CKR,WKR,MR,NR
      READ(5,1100) KAT,KWAT,KPQT,CAT,WBT,QT
      WRITE(6,1202)KAT,KWAT,KPQT,CAT,WBT,QT
      READ(5,1100) KAR,KWAR,KPQR,CAR,WBR,QR
      WRITE(6,1203)KAR,KWAR,KPQR,CAR,WBR,QR
      READ(5,1100) KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      WRITE(6,1204)KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      READ(5,1100) KFM,KM,KPM,CKM,WKM
      WRITE(6,1205)KFM,KM,KPM,CKM,WKM
      READ(5,1100) KFD,KD,KPD,CKD,WKD
      WRITE(6,1206)KFD,KD,KPD,CKD,WKD
      READ (5,1100) KST,KWST,CKE,WKE
      WRITE(6,1207) KST,KWST,CKE,WKE
      READ(5,1100) KSR,KWSR,CKF,WKF
      WRITE(6,1208)KSR,KWSR,CKF,WKF
      READ(5,1100) H,C
      WRITE(6,1210) H,C
      READ(5,1100) KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      WRITE(6,1209)KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      KN = .3*ETA*TAUT*TAUA*TAUR/((R**2 * H)*C *LAMBDA*SN)
      K  = (1.22E-23*R**2)* QB*LAMBDA*LMBDI/TAUT
      KMT = KTHT
      KNT = KDT*(KS*(1.+KWAT)+ KPQT*KWAT*(KST+KS*KWST))
      KQT = KAT/LAMBDA**QT
      KMR = KTHR
      KNR = KDR*(KS*(1.+ KWAR) +KPQR*KWAR*(KSR + KS*KWSR))
      KGT = KPT
      KHT = KS*KWT
      KJT = KS*(KWST/KE + KX*(1.-KE)/KE) + KST/KE + KH*(1.-KE)/KE
      KQR = KAR
      WRITE (6,2000)KN,K,KMT,KNT,KQT,KMR,KNR,KQR,KGT,KHT,KJT
      READ (5,1100) DTI,DRI,PTI,THERI,CVI,CVMIN
      CV = CVI
      DELCV = CV/10.
      DT = DTI
      PT = PTI
```

```
      DR = DRI
      THER = THERI
      WRITE (6,2001) THER,DT,DR,PT,CV
    8 PCTPDT =(MT*KMT*DT**MT + NT*KNT*DT**NT +QT*KQT*DT**QT)/DT
   10 PCGPPT =(GT*KGT*PT**GT + HT*KHT*PT**HT)/PT + KJT
      F1 = DT*PCTPDT
      F2 =  2.*PT * PCGPPT
      T  = F1 - F2
      IF((F1/F2) .GT. .999995 .AND. (F1/F2) .LT. 1.000005 ) GO TO 60
      PCGPT2 = (GT*(GT-1.)*KGT*PT**GT +HT*(HT-1.)*KHT*PT**HT)/PT**2
      DELPT  = T/(2.*(PT*PCGPT2 +PCGPPT))
      XXX = PT + DELPT
      IF(XXX .LT. 0.) XXX = PT/2.
      PT = XXX
      GO TO 10
   60 CONTINUE
   80 PCRPDR = (MR*KMR*DR**MR +   NR*KNR*DR**NR)/DR
      F1 =  DT*PCTPDT
      F2 = DR*PCRPDR
      W = F1 - F2
      IF((F1/F2) .GT. .999995 .AND. (F1/F2) .LT. 1.000005 )GO TO 100
      PCRDR2 =(MR*(MR-1.)*KMR*DR**MR +NR*(NR-1.)*KNR*DR**NR)/DR**2
      DELDR = W/(DR*PCRDR2 + PCRPDR)
      XXX= DR + DELDR
      IF( XXX .LT. 0. ) XXX = DR/2.
      DR = XXX
      GO TO 80
  100 CT = KMT*DT**MT +KNT*DT**NT +KQT*DT**QT
      CR = KMR*DR**MR +KNR*DR**NR
      CG =  KGT*PT**GT  + KHT*PT**HT + KJT*PT
      CQ = KQR*THER**(-QR)
      CVA = CT+ CR + CG + CQ
      IF((CV/CVA) .GT. .99995 .AND. (CV/CVA) .LT. 1.00005 ) GO TO 280
      PCTPDT = (MT*KMT*DT**MT + NT*KNT*DT**NT + QT*KQT*DT**QT)/DT
      PCRPDR = (MR*KMR*DR**MR + NR*KNR*DR**NR )/DR
      PCGPPT = (GT*KGT*PT**GT + HT*KHT*PT**HT )/PT + KJT
      PCTDT2 = (MT*KMT*(MT-1.)*DT**MT  + NT*(NT-1.)*KNT*DT**NT + QT*
     *                                  (QT-1.)*KQT*DT**QT)/DT**2
      PCRDR2 =(MR*(MR-1.)*KMR*DR**MR + NR*(NR-1.)*KNR*DR**NR)/DR**2
      PCGPT2 =(GT*(GT-1.)*KGT*PT**GT + HT*(HT-1.)*KHT*PT**HT)/PT**2
      PPTPDT =(DT*PCTDT2 +PCTPDT)/(2.*PCGPPT+ 2.*PT*PCGPT2)
      PDRPDT = (DT*PCTDT2 + PCTPDT)/(PCRPDR + DR*PCRDR2)
      DELDT  = (CV-CVA)/( PCTPDT +PCRPDR*PDRPDT +PCGPPT*PPTPDT)
      XXX = DELDT +DT
      IF( XXX .LT. 0. ) XXX = DT/2.
      DT = XXX
      GO TO 8
  280 DTO = DT
      PTO = PT
      DRO = DR
      THERO = THER
      RB = KM*DTO**4*DRO**4*PTO**2
      CALL OUTPUT(DTO,DRO,PTO,THERO,RB)
      IF(CV .LE. CVMIN) GO TO 370
      IF(CV .EQ. DELCV) DELCV = DELCV/10.
      CV = CV - DELCV
      GO TO 8
```

EXHIBIT A2. 6-2 (continued)

```
 370 STOP
1100 FORMAT (6F12.5)
1200 FORMAT (15H1 TRANSMITTER   ,5H KTHT,E13.5,5H KDT ,E13.5,5H CKT ,E13
    *.5,5H WKT ,E13.5,5H MT   ,E13.5,5H NT   ,E13.5/15H  ANTENNA      //)
1201 FORMAT (15H  RECEIVER      ,5H KTHR,E13.5,5H KDR ,E13.5,5H CKR ,E13
    *.5,5H WKR ,E13.5,5H MR   ,E13.5,5H NR   ,E13.5/15H  ANTENNA      //)
1202 FORMAT (15H  TRANSMITTER   ,5H KAT ,E13.5,5H KWAT,E13.5,5H KPQT,E13
    *.5,5H CAT ,E13.5,5H WBT ,E13.5,5H QT   ,E13.5/15H  ACQUISITION  /
    *                                             15H  AND TRACK    /
    *                                             15H  SYSTEM       //)
1203 FORMAT (15H  RECEIVER      ,5H KAR ,E13.5,5H KWAR,E13.5,5H KPQR,E13
    *.5,5H CAR ,E13.5,5H WBR ,E13.5,5H QR   ,E13.5/15H  ACQUISITION  /
    *                                             15H  AND TRACK
    *                                            /15H  SYSTEM       //)
1204 FORMAT (15H  TRANSMITTER   ,5H KPT ,E13.5,5H KWT ,E13.5,5H KH  ,E13
    *.5,5H KX  ,E13.5,5H KE  ,E13.5,5H CKP ,E13.5/15X,5H CKH ,E13.5,5H
    *WKP ,E13.5,5H WKH ,E13.5,5H PKT ,E13.5,5H GT  ,E13.5,5H HT  ,E13.5
    *                                                                //)
1205 FORMAT (15H  MODULATION    ,5H KFM ,E13.5,5H KM  ,E13.5,5H KPM ,E13
    *.5,5H CKM ,E13.5,5H WKM ,E13.5/15H  EQUIPMENT    //)
1206 FORMAT (15H  DEMODULATION  ,5H KFD ,E13.5,5H KD  ,E13.5,5H KPD ,E13
    *.5,5H CKD ,E13.5,5H WKD ,E13.5/15H  EQUIPMENT    //)
1207 FORMAT (15H  TRANSMITTER   ,5H KST ,E13.5,5H KWST,E13.5,5H CKF ,E13
    *.5,5H WKF ,E13.5/15H  POWER SUPPLY //)
1208 FORMAT (15H  RECEIVER      ,5H KSR ,E13.5,5H KWSR,E13.5,5H CKF ,E13
    *.5,5H WKF ,E13.5/15H  POWER SUPPLY //)
1209 FORMAT ( 7H  KS = ,E13.5,11H  LAMBDA = ,E13.5,13H  LAMBDA I = ,E13
    *.5,6H  R = ,E13.5,10H  TAU T = ,E13.5//10H  TAU R = ,E13.5,10H  TA
    *U A = ,E13.5, 8H  ETA = ,E13.5,11H  (S/N) = ,E13.5,7H  QB = ,E13.
    *5/2H1 )
1210 FORMAT(7H    H = ,E13.5,7H    C = ,E13.5//)
2000 FORMAT( 7H1 KN = ,E18.8,7H    K = ,E18.8,7H KMT = ,E18.8,7H KNT = ,
    * E18.8,7H KQT = ,E18.8/ 7H KMR = ,E18.8,7H KNR = ,E18.8,7H KQR = ,
    * E18.8,7H KGT = ,E18.8, 7H KHT = ,E18.8/7H KJT = ,E18.8///)
2001 FORMAT(53X,23HINITIAL CONDITIONS DATA//11H THETA-R = ,E12.5,
    * 6H DT = ,E12.5,6H DR = ,E12.5,6H PT = ,E12.5,6H CV = ,E12.5// )
     END
```

APPENDIX A2. 7

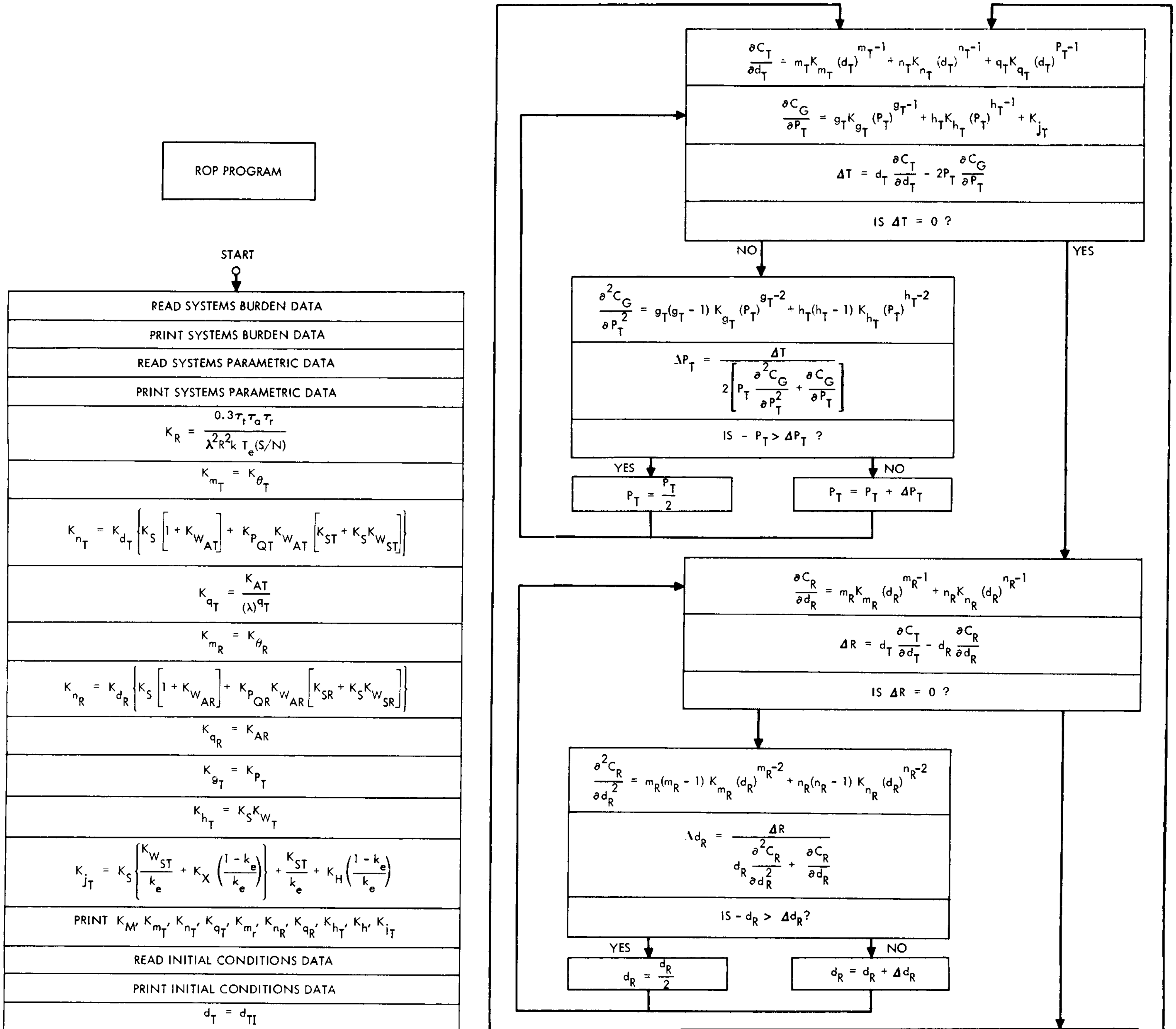
RADIO RECEIVER OPTIMIZATION PROGRAM WITHOUT COMPONENT STOPS (ROP)

FUNCTION

The function of the ROP program is to determine the optimum values of the major system parameters as a function of information rate for a radio receiver.

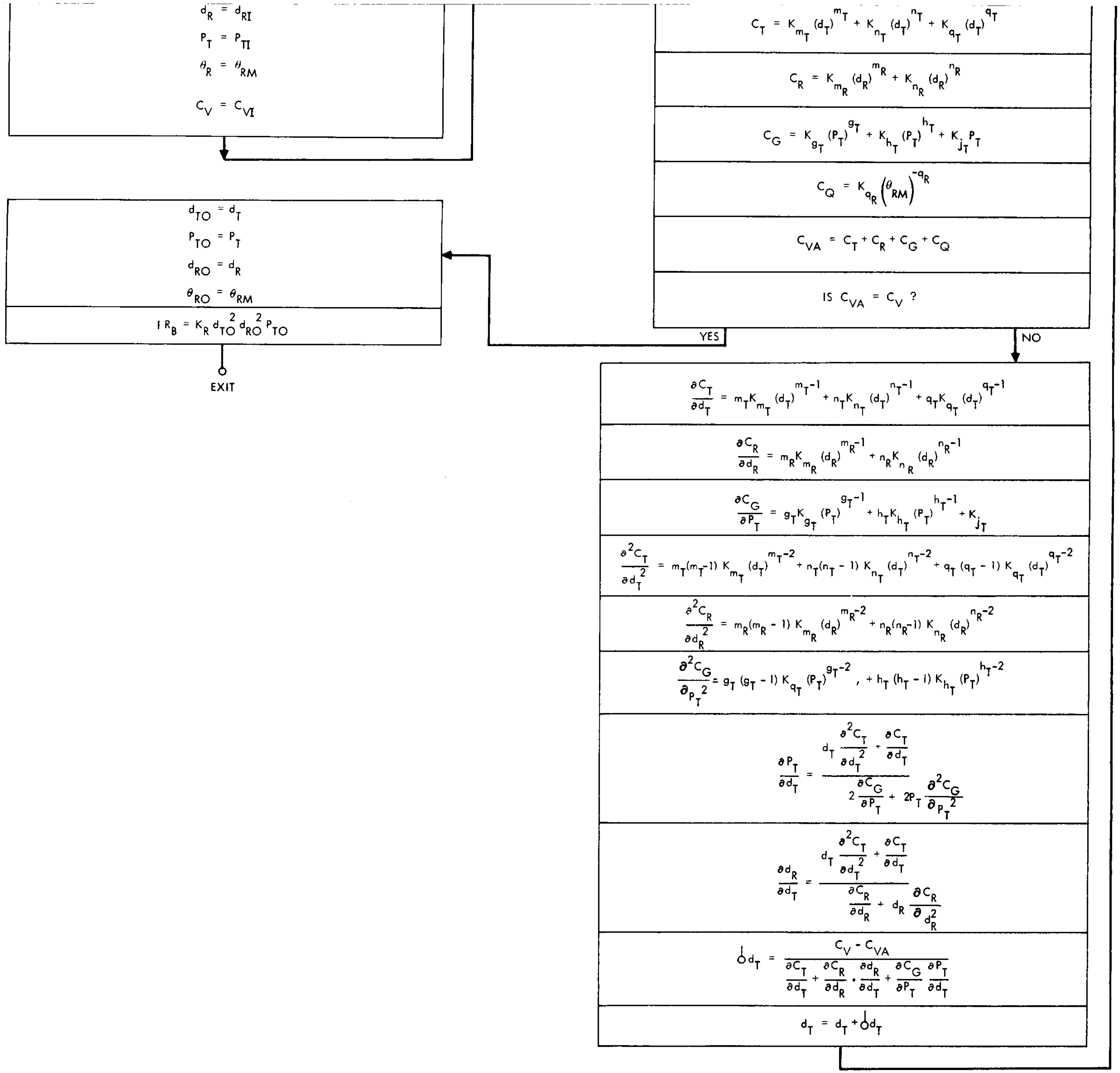
DESCRIPTION

Exhibit A2. 7-1 is a detailed flow chart of the ROP optimization program. The input information required for the program is the systems burdens data, the systems parametric data, and the initial conditions data. Exhibit A2. 7-2 contains a listing of the Fortran IV ROP program.



ROP PROGRAM
START
READ SYSTEMS BURDEN DATA
PRINT SYSTEMS BURDEN DATA
READ SYSTEMS PARAMETRIC DATA
PRINT SYSTEMS PARAMETRIC DATA
$K_R = \frac{0.3\tau_t\tau_a\tau_r}{\lambda^2 R^2 k\, T_e (S/N)}$
$K_{m_T} = K_{\theta_T}$
$K_{n_T} = K_{d_T}\left\{K_S\left[1 + K_{W_{AT}}\right] + K_{P_{QT}} K_{W_{AT}}\left[K_{ST} + K_S K_{W_{ST}}\right]\right\}$
$K_{q_T} = \frac{K_{AT}}{(\lambda)^{q_T}}$
$K_{m_R} = K_{\theta_R}$
$K_{n_R} = K_{d_R}\left\{K_S\left[1 + K_{W_{AR}}\right] + K_{P_{QR}} K_{W_{AR}}\left[K_{SR} + K_S K_{W_{SR}}\right]\right\}$
$K_{q_R} = K_{AR}$
$K_{g_T} = K_{P_T}$
$K_{h_T} = K_S K_{W_T}$
$K_{j_T} = K_S\left\{\frac{K_{W_{ST}}}{k_e} + K_X\left(\frac{1-k_e}{k_e}\right)\right\} + \frac{K_{ST}}{k_e} + K_H\left(\frac{1-k_e}{k_e}\right)$
PRINT $K_M, K_{m_T}, K_{n_T}, K_{q_T}, K_{m_r}, K_{n_R}, K_{q_R}, K_{h_T}, K_h, K_{i_T}$
READ INITIAL CONDITIONS DATA
PRINT INITIAL CONDITIONS DATA
$d_T = d_{TI}$
$\frac{\partial C_T}{\partial d_T} = m_T K_{m_T}(d_T)^{m_T-1} + n_T K_{n_T}(d_T)^{n_T-1} + q_T K_{q_T}(d_T)^{P_T-1}$
$\frac{\partial C_G}{\partial P_T} = g_T K_{g_T}(P_T)^{g_T-1} + h_T K_{h_T}(P_T)^{h_T-1} + K_{j_T}$
$\Delta T = d_T \frac{\partial C_T}{\partial d_T} - 2P_T \frac{\partial C_G}{\partial P_T}$
IS $\Delta T = 0$?
NO
YES
$\frac{\partial^2 C_G}{\partial P_T^2} = g_T(g_T - 1) K_{g_T}(P_T)^{g_T-2} + h_T(h_T - 1) K_{h_T}(P_T)^{h_T-2}$
$\Delta P_T = \frac{\Delta T}{2\left[P_T \frac{\partial^2 C_G}{\partial P_T^2} + \frac{\partial C_G}{\partial P_T}\right]}$
IS $- P_T > \Delta P_T$?
YES
NO
$P_T = \frac{P_T}{2}$
$P_T = P_T + \Delta P_T$
$\frac{\partial C_R}{\partial d_R} = m_R K_{m_R}(d_R)^{m_R-1} + n_R K_{n_R}(d_R)^{n_R-1}$
$\Delta R = d_T \frac{\partial C_T}{\partial d_T} - d_R \frac{\partial C_R}{\partial d_R}$
IS $\Delta R = 0$?
$\frac{\partial^2 C_R}{\partial d_R^2} = m_R(m_R - 1) K_{m_R}(d_R)^{m_R-2} + n_R(n_R - 1) K_{n_R}(d_R)^{n_R-2}$
$\Delta d_R = \frac{\Delta R}{d_R \frac{\partial^2 C_R}{\partial d_R^2} + \frac{\partial C_R}{\partial d_R}}$
IS $- d_R > \Delta d_R$?
YES
NO
$d_R = \frac{d_R}{2}$
$d_R = d_R + \Delta d_R$

A2.7-2



$d_R = d_{RI}$
$P_T = P_{TI}$
$\theta_R = \theta_{RM}$
$C_V = C_{VI}$
$C_T = K_{m_T} (d_T)^{m_T} + K_{n_T} (d_T)^{n_T} + K_{q_T} (d_T)^{q_T}$
$C_R = K_{m_R} (d_R)^{m_R} + K_{n_R} (d_R)^{n_R}$
$C_G = K_{g_T} (P_T)^{g_T} + K_{h_T} (P_T)^{h_T} + K_{j_T} P_T$
$C_Q = K_{q_R} \left(\theta_{RM}\right)^{-q_R}$
$C_{VA} = C_T + C_R + C_G + C_Q$
IS $C_{VA} = C_V$?
YES
NO
$d_{TO} = d_T$
$P_{TO} = P_T$
$d_{RO} = d_R$
$\theta_{RO} = \theta_{RM}$
$I R_B = K_R d_{TO}^2 d_{RO}^2 P_{TO}$
EXIT
$\frac{\partial C_T}{\partial d_T} = m_T K_{m_T} (d_T)^{m_T - 1} + n_T K_{n_T} (d_T)^{n_T - 1} + q_T K_{q_T} (d_T)^{q_T - 1}$
$\frac{\partial C_R}{\partial d_R} = m_R K_{m_R} (d_R)^{m_R - 1} + n_R K_{n_R} (d_R)^{n_R - 1}$
$\frac{\partial C_G}{\partial P_T} = g_T K_{g_T} (P_T)^{g_T - 1} + h_T K_{h_T} (P_T)^{h_T - 1} + K_{j_T}$
$\frac{\partial^2 C_T}{\partial d_T^2} = m_T(m_T - 1) K_{m_T} (d_T)^{m_T - 2} + n_T(n_T - 1) K_{n_T} (d_T)^{n_T - 2} + q_T (q_T - 1) K_{q_T} (d_T)^{q_T - 2}$
$\frac{\partial^2 C_R}{\partial d_R^2} = m_R(m_R - 1) K_{m_R} (d_R)^{m_R - 2} + n_R(n_R - 1) K_{n_R} (d_R)^{n_R - 2}$
$\frac{\partial^2 C_G}{\partial P_T^2} = g_T (g_T - 1) K_{q_T} (P_T)^{g_T - 2} , + h_T (h_T - 1) K_{h_T} (P_T)^{h_T - 2}$
$\frac{\partial P_T}{\partial d_T} = \frac{d_T \frac{\partial^2 C_T}{\partial d_T^2} + \frac{\partial C_T}{\partial d_T}}{2 \frac{\partial C_G}{\partial P_T} + 2P_T \frac{\partial^2 C_G}{\partial P_T^2}}$
$\frac{\partial d_R}{\partial d_T} = \frac{d_T \frac{\partial^2 C_T}{\partial d_T^2} + \frac{\partial C_T}{\partial d_T}}{\frac{\partial C_R}{\partial d_R} + d_R \frac{\partial C_R}{\partial d_R^2}}$
$\delta d_T = \frac{C_V - C_{VA}}{\frac{\partial C_T}{\partial d_T} + \frac{\partial C_R}{\partial d_R} \cdot \frac{\partial d_R}{\partial d_T} + \frac{\partial C_G}{\partial P_T} \frac{\partial P_T}{\partial d_T}}$
$d_T = d_T + \delta d_T$

EXHIBIT A2.7-2

```
CHCP         OPTIMIZATION METHODOLOGY ROP PROGRAM

      REAL KTHT, KDT,  MT,  NT,KTHR, KDR,  MR,  NR, KAT,KWAT,KPQT, KAR
      REAL KWAR,KPQR, KPT, KWT,  KH,  KX,  KE, KFM,  KM, KPM, KFD,  KD
      REAL  KPD, KST,KWST, KSR,KWSR,  KS, KHT, KJT, KGT, KMT, KNT, KQT
      REAL  KMR, KNR, KQR,LAMBDA,LMBDI,K,KN
      COMMON/TRANT/ KTHT,KDT,CKT,WKT,MT,NT
      COMMON/RCANT/ KTHR,KDR,CKR,WKR,MR,NR
      COMMON/TACTS/ KAT,KWAT,KPQT,CAT,WBT,QT
      COMMON/RACTS/ KAR,KWAR,KPQR,CAR,WBR,QR
      COMMON/TRNSM/ KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      COMMON/EQMOD/ KFM,KM,KPM,CKM,WKM
      COMMON/EQDMD/ KFD,KD,KPD,CKD,WKD
      COMMON/TRNPS/ KST,KWST,CKE,WKE
      COMMON/RCVPS/KSR,KWSR,CKF,WKF
      COMMON/GENRL/ KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      COMMON/OUTPT/ KHT,KJT,KGT,KMT,KNT,KQT,KMR,KNR,KQR
      READ(5,1100) KTHT,KDT,CKT,WKT,MT,NT
      WRITE(6,1200)KTHT,KDT,CKT,WKT,MT,NT
      READ(5,1100) KTHR,KDR,CKR,WKR,MR,NR
      WRITE(6,1201)KTHR,KDR,CKR,WKR,MR,NR
      READ(5,1100) KAT,KWAT,KPQT,CAT,WBT,QT
      WRITE(6,1202)KAT,KWAT,KPQT,CAT,WBT,QT
      READ(5,1100) KAR,KWAR,KPQR,CAR,WBR,QR
      WRITE(6,1203)KAR,KWAR,KPQR,CAR,WBR,QR
      READ(5,1100) KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      WRITE(6,1204)KPT,KWT,KH,KX,KE,CKP,CKH,WKP,WKH,PKT,GT,HT
      READ(5,1100) KFM,KM,KPM,CKM,WKM
      WRITE(6,1205)KFM,KM,KPM,CKM,WKM
      READ(5,1100) KFD,KD,KPD,CKD,WKD
      WRITE(6,1206)KFD,KD,KPD,CKD,WKD
      READ (5,1100) KST,KWST,CKE,WKE
      WRITE(6,1207) KST,KWST,CKE,WKE
      READ(5,1100) KSR,KWSR,CKF,WKF
      WRITE(6,1208)KSR,KWSR,CKF,WKF
      READ (5,1100) SMK,TE
      WRITE(6,1210) SMK,TE
      READ(5,1100) KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      WRITE(6,1209)KS,LAMBDA,LMBDI,R,TAUT,TAUR,TAUA,ETA,SN,QB
      KR = (.3*TAUR*TAUA*TAUT)/(LAMBDA**2 *(R**2 * SMK) * TE * SN)
      KMT = KTHT
      KNT = KDT*(KS*(1.+KWAT)+ KPQT*KWAT*(KST+KS*KWST))
      KQT = KAT/LAMBDA**QT
      KMR = KTHR
      KNR = KDR*(KS*(1.+ KWAR) +KPQR*KWAR*(KSR + KS*KWSR))
      KGT = KPT
      KHT = KS*KWT
      KJT = KS*(KWST/KE + KX*(1.-KE)/KE) + KST/KE + KH*(1.-KE)/KE
      KQR = KAR
      WRITE (6,2000)KN,K,KMT,KNT,KQT,KMR,KNR,KQR,KGT,KHT,KJT
      READ (5,1100) DTI,DRI,PTI,THERI,CVI,CVMIN
      CV = CVI
      DELCV = CV/10.
      DT = DTI
      PT = PTI
      DR = DRI
```

EXHIBIT A2.7-2 (continued)

```
      THER = THERI
      WRITE (6,2001) THER,DT,DR,PT,CV
    8 PCTPDT =(MT*KMT*DT**MT + NT*KNT*DT**NT +QT*KQT*DT**QT)/DT
   10 PCGPPT =(GT*KGT*PT**GT + HT*KHT*PT**HT)/PT + KJT
      F1 = DT*PCTPDT
      F2 =  2.*PT * PCGPPT
      T  = F1 - F2
      IF((F1/F2) .GT. .999995 .AND. (F1/F2) .LT. 1.000005 ) GO TO 60
      PCGPT2 = (GT*(GT-1.)*KGT*PT**GT +HT*(HT-1.)*KHT*PT**HT)/PT**2
      DELPT  = T/(2.*(PT*PCGPT2 +PCGPPT))
      XXX = PT + DELPT
      IF(XXX .LT. 0.) XXX = PT/2.
      PT = XXX
      GO TO 10
   60 CONTINUE
   80 PCRPDR = (MR*KMR*DR**MR +   NR*KNR*DR**NR)/DR
      F1 =  DT*PCTPDT
      F2 = DR*PCRPDR
      W = F1 - F2
      IF((F1/F2) .GT. .999995 .AND. (F1/F2) .LT. 1.000005 )GO TO 100
      PCRDR2 =(MR*(MR-1.)*KMR*DR**MR +NR*(NR-1.)*KNR*DR**NR)/DR**2
      DELDR = W/(DR*PCRDR2 + PCRPDR)
      XXX= DR + DELDR
      IF( XXX .LT. 0. ) XXX = DR/2.
      DR = XXX
      GO TO 80
  100 CT = KMT*DT**MT +KNT*DT**NT +KQT*DT**QT
      CR = KMR*DR**MR +KNR*DR**NR
      CG =  KGT*PT**GT  + KHT*PT**HT + KJT*PT
      CQ = KQP*THER**(-QR)
      CVA = CT+ CR + CG + CQ
      IF((CV/CVA) .GT. .99995 .AND. (CV/CVA) .LT. 1.00005 ) GO TO 280
      PCTPDT = (MT*KMT*DT**MT + NT*KNT*DT**NT + QT*KQT*DT**QT)/DT
      PCRPDR = (MR*KMR*DR**MR + NR*KNR*DR**NR )/DR
      PCGPPT = (GT*KGT*PT**GT + HT*KHT*PT**HT )/PT + KJT
      PCTDT2 = (MT*KMT*(MT-1.)*DT**MT  + NT*(NT-1.)*KNT*DT**NT + QT*
     *                                     (QT-1.)*KQT*DT**QT)/DT**2
      PCRDR2 =(MR*(MR-1.)*KMR*DR**MR + NR*(NR-1.)*KNR*DR**NR)/DR**2
      PCGPT2 =(GT*(GT-1.)*KGT*PT**GT + HT*(HT-1.)*KHT*PT**HT)/PT**2
      PPTPDT =(DT*PCTDT2 +PCTPDT)/(2.*PCGPPT+ 2.*PT*PCGPT2)
      PDRPDT = (DT*PCTDT2 + PCTPDT)/(PCRPDR + DR*PCRDR2)
      DELDT  = (CV-CVA)/( PCTPDT +PCRPDR*PDRPDT +PCGPPT*PPTPDT)
      XXX = DELDT +DT
      IF( XXX .LT. 0. ) XXX = DT/2.
      DT = XXX
      GO TO 8
  280 DTO = DT
      PTO = PT
      DRO = DR
      THERO = THER
      RB = KR*DTO**2 *DRO**2 *PTO
      CALL OUTPUT(DTO,DRO,PTO,THERO,RB)
      IF(CV .LE. CVMIN) GO TO 370
      IF(CV .EQ. DELCV) DELCV = DELCV/10.
      CV = CV - DELCV
      GO TO 8
  370 STOP
```

EXHIBIT A2. 7-2 (continued)

```
1100 FORMAT (6E12.5)
1200 FORMAT (15H1 TRANSMITTER   ,5H KTHT,E13.5,5H KDT ,E13.5,5H CKT ,E13
    *.5,5H WKT ,E13.5,5H MT   ,E13.5,5H NT   ,E13.5/15H  ANTENNA      //)
1201 FORMAT (15H  RECEIVER      ,5H KTHR,E13.5,5H KDR ,E13.5,5H CKR ,E13
    *.5,5H WKR ,E13.5,5H MR   ,E13.5,5H NR   ,E13.5/15H  ANTENNA      //)
1202 FORMAT (15H  TRANSMITTER   ,5H KAT ,E13.5,5H KWAT,E13.5,5H KPQT,E13
    *.5,5H CAT ,E13.5,5H WBT  ,E13.5,5H QT   ,E13.5/15H  ACQUISITION  /
    *                                              15H  AND TRACK    /
    *                                              15H  SYSTEM       //)
1203 FORMAT (15H  RECEIVER      ,5H KAR ,E13.5,5H KWAR,E13.5,5H KPQR,E13
    *.5,5H CAR ,E13.5,5H WBR  ,E13.5,5H QR   ,E13.5/15H  ACQUISITION  /
    *                                              15H  AND TRACK
    *                                             /15H  SYSTEM       //)
1204 FORMAT (15H  TRANSMITTER   ,5H KPT ,E13.5,5H KWT ,E13.5,5H KH   ,E13
    *.5,5H KX   ,E13.5,5H KE   ,E13.5,5H CKP ,E13.5/15X,5H CKH ,E13.5,5H
    *WKP  ,E13.5,5H WKH  ,E13.5,5H PKT ,E13.5,5H GT   ,E13.5,5H HT   ,E13.5
    *                                                                  //)
1205 FORMAT (15H  MODULATION    ,5H KFM ,E13.5,5H KM   ,E13.5,5H KPM ,E13
    *.5,5H CKM ,E13.5,5H WKM ,E13.5/15H  EQUIPMENT     //)
1206 FORMAT (15H  DEMODULATION ,5H KFD ,E13.5,5H KD   ,E13.5,5H KPD ,E13
    *.5,5H CKD ,E13.5,5H WKD ,E13.5/15H  EQUIPMENT     //)
1207 FORMAT (15H  TRANSMITTER   ,5H KST ,E13.5,5H KWST,E13.5,5H CKE ,E13
    *.5,5H WKE ,E13.5/15H  POWER SUPPLY //)
1208 FORMAT (15H  RECEIVER      ,5H KSR ,E13.5,5H KWSR,E13.5,5H CKF ,E13
    *.5,5H WKF ,E13.5/15H  POWER SUPPLY //)
1209 FORMAT ( 7H  KS = ,E13.5,11H  LAMBDA = ,E13.5,13H  LAMBDA I = ,E13
    *.5,6H  R = ,E13.5,10H  TAU T = ,E13.5//10H  TAU R = ,E13.5,10H  TA
    *U A = ,E13.5, 8H  ETA = ,E13.5,11H   (S/N) = ,E13.5,7H  QB = ,E13.
    *5/2H1 )
1210 FORMAT(7H SMK = ,E13.5,7H  TE = ,E13.5)
2000 FORMAT( 7H1 KN = ,E18.8,7H   K = ,E18.8,7H KMT = ,E18.8,7H KNT = ,
    * E18.8,7H KQT = ,E18.8/ 7H KMR = ,E18.8,7H KNR = ,E18.8,7H KQR = ,
    * E18.8,7H KGT = ,E18.8, 7H KHT = ,E18.8/7H KJT = ,E18.8///)
2001 FORMAT(53X,23HINITIAL CONDITIONS DATA//11H THETA-R = ,E12.5,
    * 6H DT = ,E12.5,6H DR = ,E12.5,6H PT = ,E12.5,6H CV = ,E12.5// )
     END
```

14.0 HEAT REJECTION SYSTEMS

14.1 INTRODUCTION

The spacecraft thermal control system requirements imposed by the communication system and the resulting cost, weight, and area burdens are presented in this section. The communication system characteristics which determine the thermal control requirements are the output power, efficiency, and operating temperature of the transmitting source. In addition, the thermal control system burden is also influenced by the mission thermal environment and the spacecraft configuration.

14.2 COMMUNICATION SYSTEM HEAT REJECTION REQUIREMENTS

14.2.1 General Considerations

Since operation of the transmitter will not be continuous throughout the mission, the steady state thermal control of the spacecraft must of necessity be independent of rejected transmitter heat. Thus, essentially all the heat produced by intermittent operation of the transmitter must be rejected from the spacecraft. The power to be rejected, W, is then

$$W = P_T \frac{1 - k_e}{k_e}$$

where

P_T = transmitter output power

k_e = transmitter efficiency

This approximation of rejected heat burden is totally conservative since it is assumed that none of the power rejected by the transmitter may be put to effective use in thermal control.

The system parameters of most significance in determining the radiator burden for a given transmitted power are the operating temperature of the transmitting source and its efficiency. Operating temperatures range from less than 100° F for some laser sources to 400 to 500° F for TWT microwave sources. The efficiencies vary even more widely. If the transmitter power and efficiency have been specified and if its operating temperature is known, the associated radiator weight, area, and cost burdens are essentially determined.

14.2.2 Transmitter Source Characteristics

Microwave Sources. The microwave source of greatest interest for long space missions is the traveling-wave amplifier tube (TWT), Figure 14-1. The greatest heat is generated at the collector surface of the TWT. These parts may reach temperatures as high as 400 to 500° F in present long life tubes. For lower power levels (less than 100 to 200 watts output) it is customary to conductively cool the collector by thermally connecting it to a heat sink, which conducts to an external radiating surface. Higher power tubes are customarily cooled by flowing a coolant fluid through integral passages in the collector and other critical parts. The upper limit in outlet fluid temperature is imposed by the collector temperature limitations although it is typically somewhat lower as a result of temperature drops in other parts of the internal tube coolant circuit.

For power levels beyond 1 kw, TWTs are generally built in a different configuration from that used at lower powers. The high power configuration uses a cavity resonator which requires a solenoid to provide the necessary magnetic field. The solenoid must be cooled as well in this case. With modern high temperature insulating materials the solenoid operating temperatures may be comparable with the collector temperature.

Traveling wave tubes operate at efficiencies as high as 30 percent including power supply losses. For high power tubes, the solenoid cooling requirement is reflected in the efficiency.

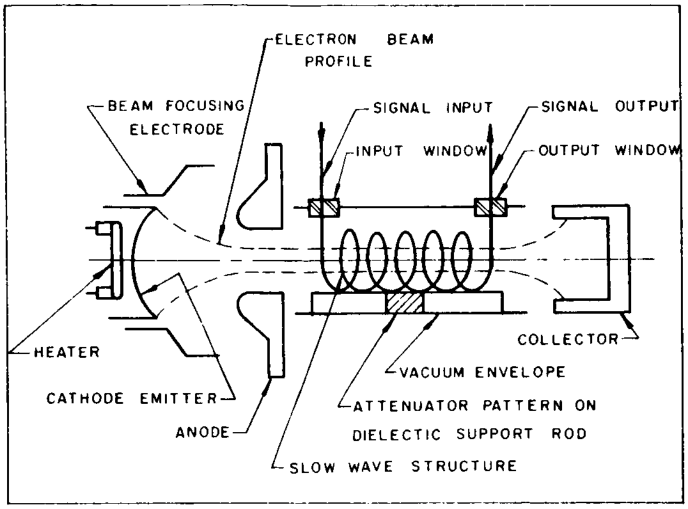


Figure 14-1. Schematic diagram showing basic parts of a traveling-wave tube.

Optical Transmitting Sources. The two optical sources of primary interest here are the CO_2 laser (10.6 μ wavelength) and the Argon laser (0.5145 μ wavelength). They differ drastically in operating efficiency and operating temperature requirements.

The CO_2 laser operates at efficiencies as high as 15 percent. To achieve this high efficiency, the gas mixture must be kept at temperatures of 20° C or less. Efficiency drops off rapidly at higher temperatures. For a typical low power device, output was reduced from 1.5 watts at 20° C to 0.7 watt at 60° C and 0.25 watt at 100° C. To maintain the required temperatures, most laboratory versions use water as a coolant, flowing it between the walls of the discharge tube and an outer concentric jacket. For the high power levels envisioned for space transmitting sources, an active fluid cooling system is virtually a necessity.

The Argon laser is characterized by efficiencies of the order of 0.1 percent or less. The very large fraction of input power which must be rejected as a result of this inefficiency demands liquid cooling for all power levels under consideration. Efficiency is not a critical function of the operating temperature as is the case with the CO_2 laser.

The upper limit in operating temperature is imposed by the limits for safe operation of the solenoid which surrounds the discharge tube and provides the pumping magnetic field. The pumping solenoid generates a large amount of heat and both it and the discharge tube must be cooled. The most effective way to achieve this is to flow the coolant fluid through the annular passage between them. Maximum operating temperatures imposed by solenoid temperature as limited by modern high temperature insulating materials may be as high as 200 to 300° F.

14.3 GENERAL HEAT REJECTION SYSTEM CONSIDERATIONS

Heat rejection systems may be classified as active or passive. In the most general sense, an active system is one which embodies moving parts (e.g., a coolant fluid or a thermal switch) while a passive system does not. In typical active systems heat is conveyed to the radiating surface by first transferring it to a fluid medium which is then physically transported to the radiator where its heat is rejected. In a passive system heat is conveyed to a radiating surface and dissipated from it by purely static processes. Passive systems usually are limited to dissipation of relatively small quantities of heat per volume in cases where an excellent thermal conductive path exists between the heat source and radiating surface.

14.4 ACTIVE HEAT REJECTION SYSTEMS

In general, the active heat rejection system consists of a heat exchanger to transfer heat from the transmitting source to the cooling fluid, the necessary plumbing to convey the fluid to the radiator, and the radiator itself. Of these, the radiator proper is the major contributor to the thermal control system cost, weight, and area burdens. The heat exchanger at the transmitting source is an integral part of the source and is characteristic of it. The burdens associated with transferring heat from the source to the cooling system are thus included in the transmitting source burdens and cannot meaningfully be divorced from them. The remaining system components – plumbing, pumps, controls and the coolant itself – are of less significance than the radiator with respect to cost, weight, and volume. They are, in any event, so peculiar to a specific vehicle and communication system configuration as to preclude meaningful treatment here.

Both condensing and non-condensing heat rejection systems will be discussed. Condensing (two phase) systems are most applicable to dynamic power systems and so are included as a matter of general interest. Non-condensing (single phase) systems appear more applicable to cooling transmitting sources since boiling of the coolant fluid in condensing systems introduces vapor pockets and would lead to local hot spots in critical areas.

The design of optimum fin and tube radiators is a fairly complicated process which has been adapted to computer optimization. Input variables typically include radiator and heat sink temperatures, power capacity, coolant pressure drops in the tubes and headers, and susceptibility to meteoroid damage during a given mission. The optimum configuration may then be determined in terms of tube length, number of tubes, fin length, fin diameter, and tube wall thickness. Optimization may be with respect to radiator specific weight (lbs/ft^2), specific heat rejection (watts/ft^2), or specific cost (dollars/ft^2), depending on the particular constraints of the mission.

14.4.1 Radiative Heat Transfer

For typical spacecraft fin and tube radiators the controlling thermal resistance is conduction and radiation in the radiator fin. Therefore, the preliminary designer need only consider heat transfer in the fin. Heat transfer from the working fluid to the fin is a second-order effect and must eventually be treated in some detail.

Radiant heat transfer from a flat surface at temperature, T, to a sink at absolute zero is described by the Stefan-Boltzmann equation:

$$Q = \epsilon \sigma T^4 \tag{14-1}$$

where

Q = radiative power (watts/ft^2)

ϵ = surface emissivity

σ = Stefan-Boltzmann constant = 5×10^{-10} watts/ft^2 °R^4

T = radiating surface temperature (°R)

For a non-zero sink temperature, this expression becomes

$$Q = \sigma \epsilon (T^4 - T_s^4) \tag{14-2}$$

where

T_s = sink temperature (°R)

If solar illumination is incident on the radiator, it must also be rejected, reducing the effective radiative heat flux (i.e., dissipation of heat produced by an on-board source) to

$$Q = \epsilon \sigma (T^4 - T_s^4) - \alpha_s H \cos \theta \tag{14-3}$$

where

α_s = surface absorptivity to solar illumination

H = solar illumination intensity (watts/ft^2)

θ = angle between the incident solar illumination and the normal to the radiator surface

ϵ = surface emissivity

A quantity termed the fin effectiveness is introduced to assist in the evaluation of the performance of a finned radiator. It is defined as the ratio of the heat rejected by the fin to that which would be rejected if the entire fin were maintained at the base temperature. Expressed mathematically:

$$\eta = \frac{\int_0^{\frac{B}{2}} T_x^4 \, dx}{\frac{B}{2} T^4} \tag{14-4}$$

where

η = fin effectiveness

B = tube spacing

T_x = temperature at a point on the fin

x = distance along fin

T = fin base temperature

This equation was derived by Coombs[1] et al., and was solved numerically on an IBM-704 computer. The results are given in Figure 14-2 as a function of the dimensionless radiation modulus M_r, defined as:

$$M_r = \frac{B^2 \epsilon \sigma T^3}{kt} \tag{14-5}$$

where

k = conductivity of fin material

t = fin thickness

By using the curve in Figure 14-2 the fin effectiveness may be evaluated for a given material, geometry, and base temperature (T). Equation (14-1) is plotted in Figure 14-3 for various values of the product $\epsilon \, \eta$ which constitutes an effective emissivity.

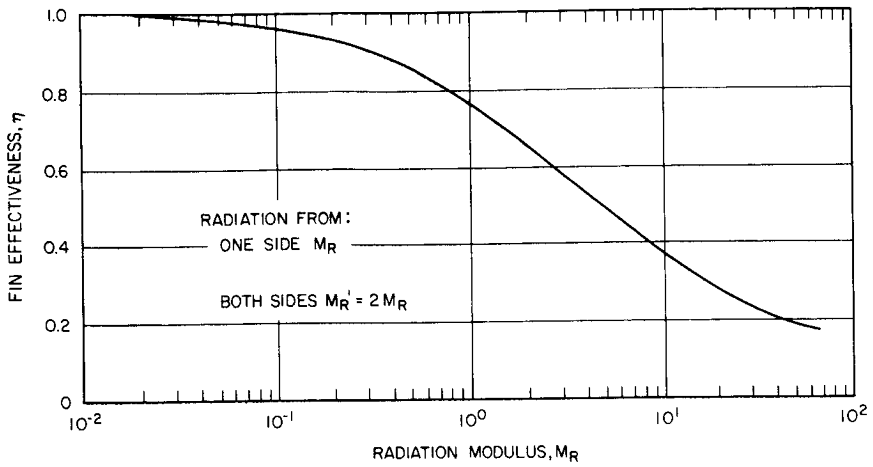


Figure 14-2. Fin effectiveness versus radiation modulus.

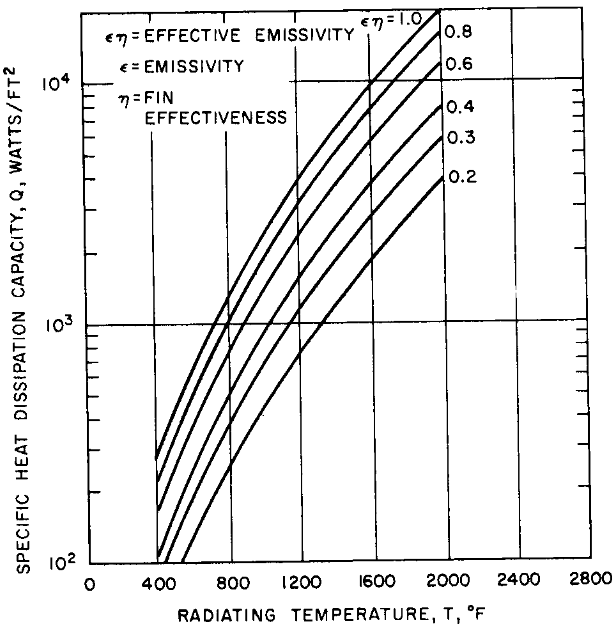


Figure 14-3. Specific heat dissipation capacity versus radiator temperature.

14.4.2 Radiator Area Requirements

Condensing Systems. For condensing radiators, the tube temperature remains constant until the fluid is completely condensed as long as the static pressure drop is kept small. This follows since the condensate and condensing vapor are always in thermal equilibrium. If this condition is met, the area requirements for the condensing portion of the radiator can be obtained by combining Equation (14-3) with the definition of fin effectiveness.

$$Q = \varepsilon \sigma \eta \left(T^4 - T_s^4\right) - \alpha_s H \cos \theta \tag{14-6}$$

Figure 14-3 can be used directly to obtain the required area if the ε as shown is considered to be equal to the product, $\varepsilon\eta$.

Non-condensing Systems. In non-condensing systems the radiant heat rejection is accompanied by a sensible heat loss of the fluid. The temperature decrease of the fluid results in temperature gradients both perpendicular and parallel to the direction of fluid flow. This complicates the analysis, but by combining the model of the condensing (constant temperature) fin with that of a radiator which experiences a coolant temperature drop, an expression can be derived to give the area requirements for the tube-fin configuration.[2] The result is given by:

$$Q = \eta \sigma \varepsilon T_{eff}^4 \tag{14-7}$$

where

Q = radiative power (watts/ft^2)

T_{in} = fluid temperature into radiator (°R)

T_{out} = fluid temperature out of radiator (°R)

$$T_{eff} = \left[\frac{3\, T_{in}^3\, T_{out}^3}{T_{in}^2 + T_{in}\, T_{out} + T_{out}^2} \right]^{1/4}$$

and

η = fin effectiveness (evaluated at T_{eff})

Equation (14-7) is plotted in Figure 14-4 for various values of T_{in} and $\Delta T = T_{in} - T_{out}$. This figure can be used to determine the area requirements for the non-condensing radiator. Using fin effectiveness and emissivity typical of non-condensing low temperature aluminum fin and tube radiators the area requirements become[3]

$$A = \frac{25.5\ W}{\left(\frac{T}{100}\right)^4} \text{ square feet} \qquad (14\text{-}8)$$

for the zero sink temperature characteristic of deep space and

$$A = \frac{25.5\ W}{\left(\frac{T}{100}\right)^4 - 320} \text{ square feet} \qquad (14\text{-}9)$$

for a sink temperature of -40°F, typical of near earth orbits.

Fin and Tube Radiator Weight and Cost Burdens. According to AiResearch Corporation,[4] low temperature radiator specific weight, assuming aluminum construction and structural rigidity as required for radiator areas greater than 50 ft^2, is approximately 0.95 lb/ft^2. For smaller radiator areas, depending on the amount of structural rigidity required, the specific weight may be as low as 0.045 lb/ft^2. Radiator heat dissipation capability versus weight is plotted in Figure 14-5 based on 0.95 lb/ft^2. Typical costs as quoted by the same source indicate development costs of $50,000, exclusive of environmental

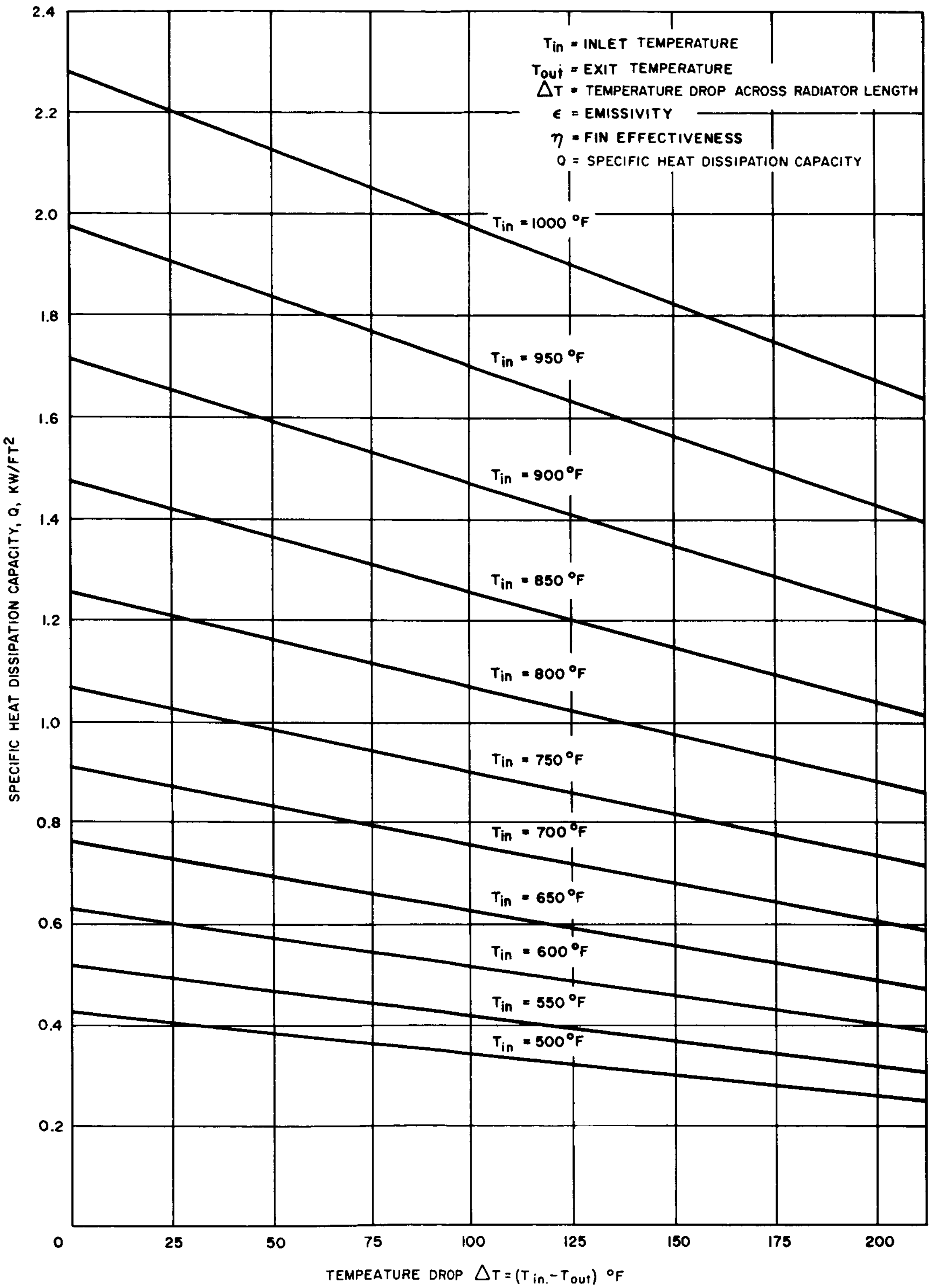


Figure 14-4. Area requirements for non-condensing radiator.

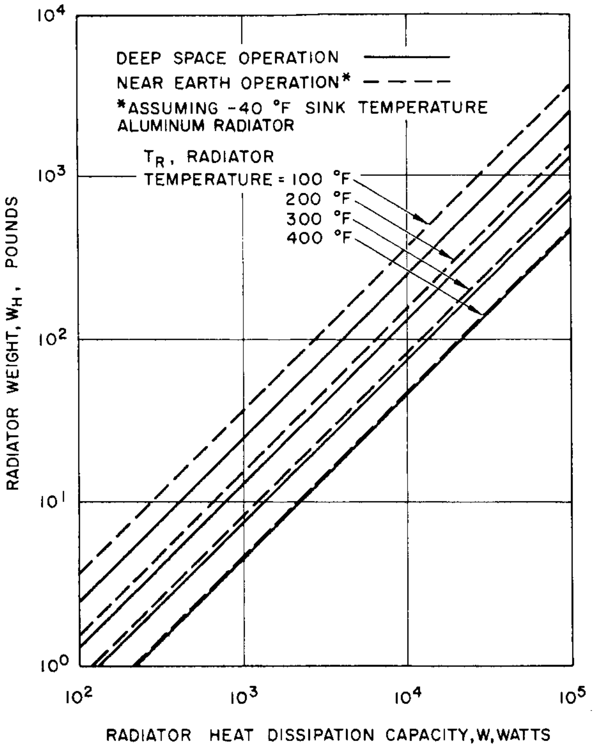


Figure 14-5. Fin and tube radiator weight, W_H (pounds), versus heat dissipation capacity at various radiator temperatures, T_R.

testing, for one 10 to 30 ft^2 space qualified radiator. For production of a number of identical radiators with the above development cost amortized over five units, an approximate functional relationship between radiator cost C_H and area of

$$C_H = \$13,750 + \$75\ A \tag{14-10}$$

can be inferred. For large production runs, with the development cost amortized over one hundred units, the radiator cost is reduced to

$$C_H = \$2,750 + 25\ A \tag{14-11}$$

Radiator heat dissipation capability versus cost for a five unit production run is plotted in Figure 14-6.

14.4.3 Pressure Drops

Condensing Systems. For both condensing and non-condensing radiators, determination of pressure drop in the coolant loop is necessary to determine the optimum tradeoff between piping diameter and coolant pump size. The design of a minimum weight condensing radiator requires an accurate prediction of the pressure drop associated with condensing in the radiator tubes. This must be done with some precision since a loss of static pressure in the condenser tubes lowers the (saturation) temperature of the working fluid, resulting in a drop in radiating power.

Viscous drag is the mechanism by which condensate is removed from a radiator-condenser. The working fluid enters the radiator-condenser as saturated vapor, and is condensed at substantially constant temperature by being subjected to a constant heat flux throughout the length of the tube. After the working fluid has been completely condensed it may be subcooled to reduce the possibility of pump cavitation, and in the case of turboelectric systems, to provide a low-temperature bearing and alternator coolant.

Many investigators have correlated pressure drop data for two-phase flow in tubes with that for single phase flow. Of these, the correlation of Lockhart and Martinelli[5] is probably the best and most widely used. They were able to correlate pressure drop for two-phase, two-component flow in the non-dimensional form:

$$\left(\frac{dP}{dL}\right)_{TPF} = \varphi_g^2 \left(\frac{dP}{dL}\right)_g, \qquad (14\text{-}12)$$

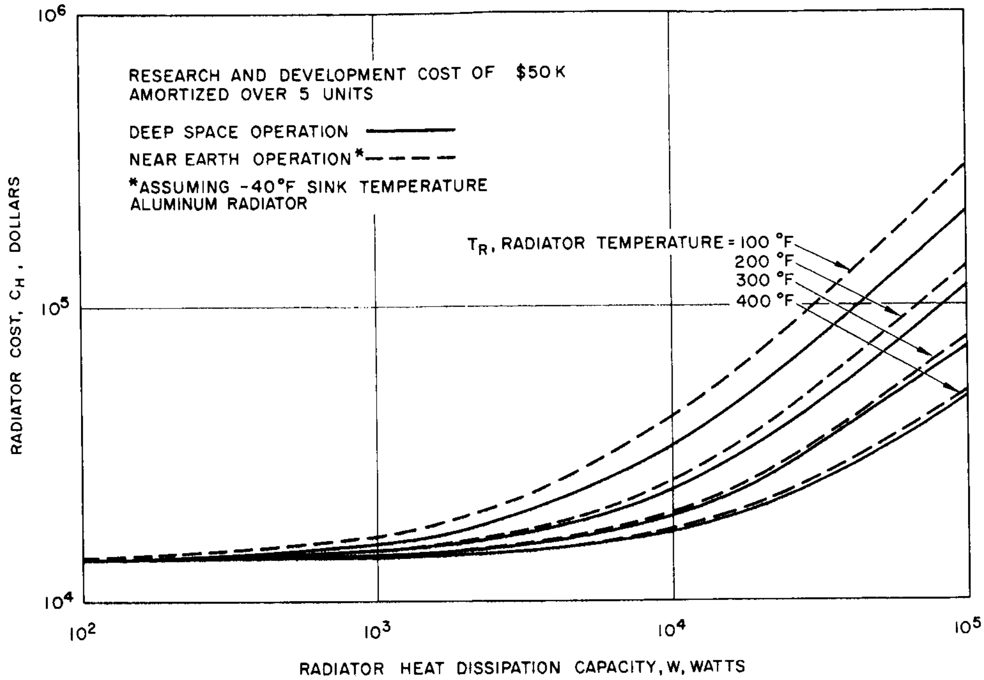


Figure 14-6. Fin and tube radiator cost, C_H, versus heat dissipation capacity at various radiator temperatures, T_R.

where

$\left(\frac{dP}{dL}\right)_{TPF}$ = two-phase frictional pressure gradient

$\left(\frac{dP}{dL}\right)_{g}$ = pressure gradient per unit tube length of the gas (vapor) phase alone

$\left(\frac{dP}{dL}\right)_{\ell}$ = pressure gradient per unit tube length of the liquid phase alone

φ_g = dimensionless parameter

The experimental data of Lockhart and Martinelli were plotted in terms of φ_g and

$$\sqrt{\frac{\left(\frac{dP}{dL}\right)_{\ell}}{\left(\frac{dP}{dL}\right)_{g}}}$$

for different combinations of flow regimes, e.g., viscous liquid-turbulent gas and turbulent liquid-turbulent gas. While these correlations were for two-component flow, extension of these correlations to boiling or condensing (i.e., two-phase one-component flow) has been suggested by Martinelli and Nelson[6] and has been tested with some success. In support of this extrapolation, McAdams[7] has found that friction arising from transfer of momentum between phases of a one-component system was of little importance under his experimental conditions. Furthermore, Lockhart and Martinelli stated that their correlation was independent of flow mechanism, whether mist, annular or stratified flow existed. Experimental work indicates that these correlations predict reasonable values for condensing pressure drop in tubes.

The Lockhart and Martinelli correlation for viscous-turbulent flow is reproduced in Figure 14-7. In the range of interest it can be represented by

$$\varphi_g = 1.76\, X^{0.0825} \tag{14-13}$$

where

$$X = \sqrt{\frac{\left(\frac{dP}{dL}\right)_\ell}{\left(\frac{dP}{dL}\right)_g}} \tag{14-14}$$

By combining Equations (14-12), (14-13), and (14-14) with the appropriate values of $(dP/dL)_g$ and integrating the resulting expression to account for the changing flow conditions throughout the length of the tube, an expression for the frictional pressure drop can be derived.[8] The result is given by:

$$\left(\frac{\Delta P}{L}\right)_{TPF} = \frac{0.402\, W_T^{\ 1.684} \mu_g^{\ 0.316}}{N^{1.684}\, D^{4.684}\, \rho_g\, g_c} \left(\frac{\rho_g\, \mu_\ell}{\rho_\ell\, \mu_g}\right)^{0.0825} \tag{14-15}$$

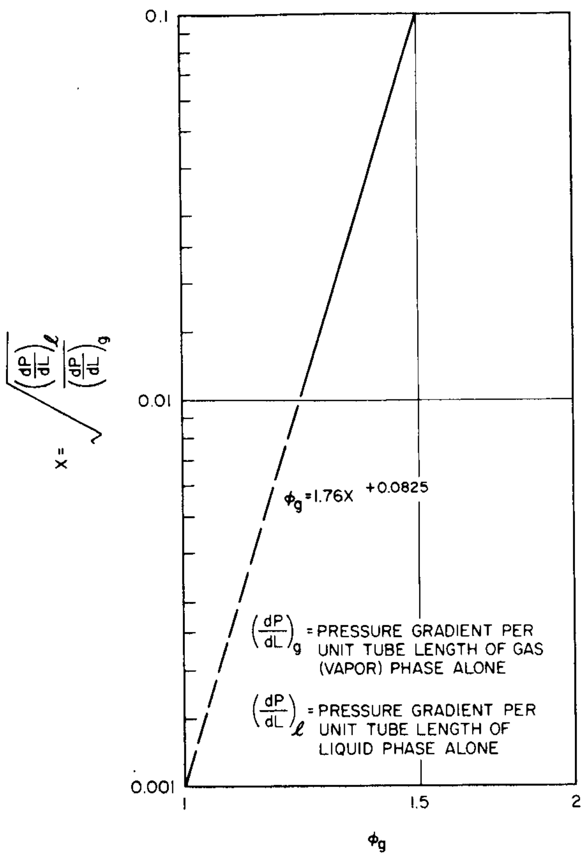


Figure 14-7. Coefficient relating the pressure gradient for two-phase flow with those for single-phase flows.

where

W_T = weight flow

μ_g = viscosity of vapor

μ_ℓ = viscosity of liquid

N = number of tubes

D = inside tube diameter

ρ_g = density of vapor

ρ_ℓ = density of liquid

g = gravitational constant

Any consistent system of units may be used.

In addition to the frictional pressure drop given by Equation (14-15), there is a pressure rise due to the momentum loss of the high velocity vapor as it traverses the condenser tube. Since the fluid velocity is essentially zero at the exit of the condenser this is given by

$$\Delta P_M = \int_{\text{inlet}}^{\text{outlet}} \rho \, u du = - \rho_g \, U_o^2 \qquad (14\text{-}16)$$

ρ = density at two phase mixture

u = velocity of two-phase mixture flow

U_o = vapor velocity at condenser inlet

or for parallel flow through N tubes

$$\Delta P_M = \left(\frac{1.62 \, W_T^{\,2}}{\rho_g \, g \quad D^4 \, N^2} \right) \qquad (14\text{-}17)$$

where the negative sign indicates a pressure rise. Equations (14-15) and (14-17) can be used to calculate the pressure drop in condensing radiators.

<u>Non-condensing Systems.</u> In non-condensing systems, which reject heat by cooling a liquid, the pressure drop is predicted by the Fanning friction equation:

$$\frac{dP}{dL} = \frac{2f \, u^2 \, \rho}{g \; D} \qquad (14\text{-}18)$$

where the friction factor, f, is given by

$$f = 0.079\ R_e^{-0.25} \qquad (14\text{-}19)$$

where R_e is the Reynolds number. For flow through N tubes in parallel:

$$\frac{\Delta P}{L} = 0.242\ \frac{W_T^{1.75}\ \mu^{0.25}}{N^{1.75}\ D^{4.75}\ \rho\ g} \qquad (14\text{-}20)$$

Equation (14-20) gives the pressure drop for a non-condensing radiator.

14.5 PASSIVE HEAT REJECTION SYSTEMS

Passive heat rejection systems are preferable when they can meet the requirements because of their extreme simplicity and concomitant lighter weight, lower cost, and higher reliability. They consist merely of a conducting path between the heat source and an external radiating surface, often a part of the spacecraft structure, having a highly emissive surface coating with low solar absorptivity. The limitation on their utility is almost always excessive temperature gradients in the conducting path as a result of thermal resistance. If the radiator is a flat surface having a uniform temperature, the heat dissipation capability is

$$Q = \epsilon\ \sigma \left(T^4 - T_s^4\right) - \alpha_s\ H \cos\theta \qquad (14\text{-}21)$$

where

Q = radiative power (watts/ft^2)

ϵ = surface emissivity

σ = Stefan-Boltzmann constant = 5×10^{-10} watts/ft^2 - °R^4
T = radiating surface temperature (°R)
T_s = sink temperature (°R)
α_s = surface absorptivity to solar illumination
H = solar illumination intensity (watts/ft^2)
θ = angle between the incident solar illumination and the normal to the radiator surface

Equation (14-21) is plotted in Figure 14-8 for various solar distances and normally incident solar illumination with α_s = 0.18 and ϵ = 0.87.*

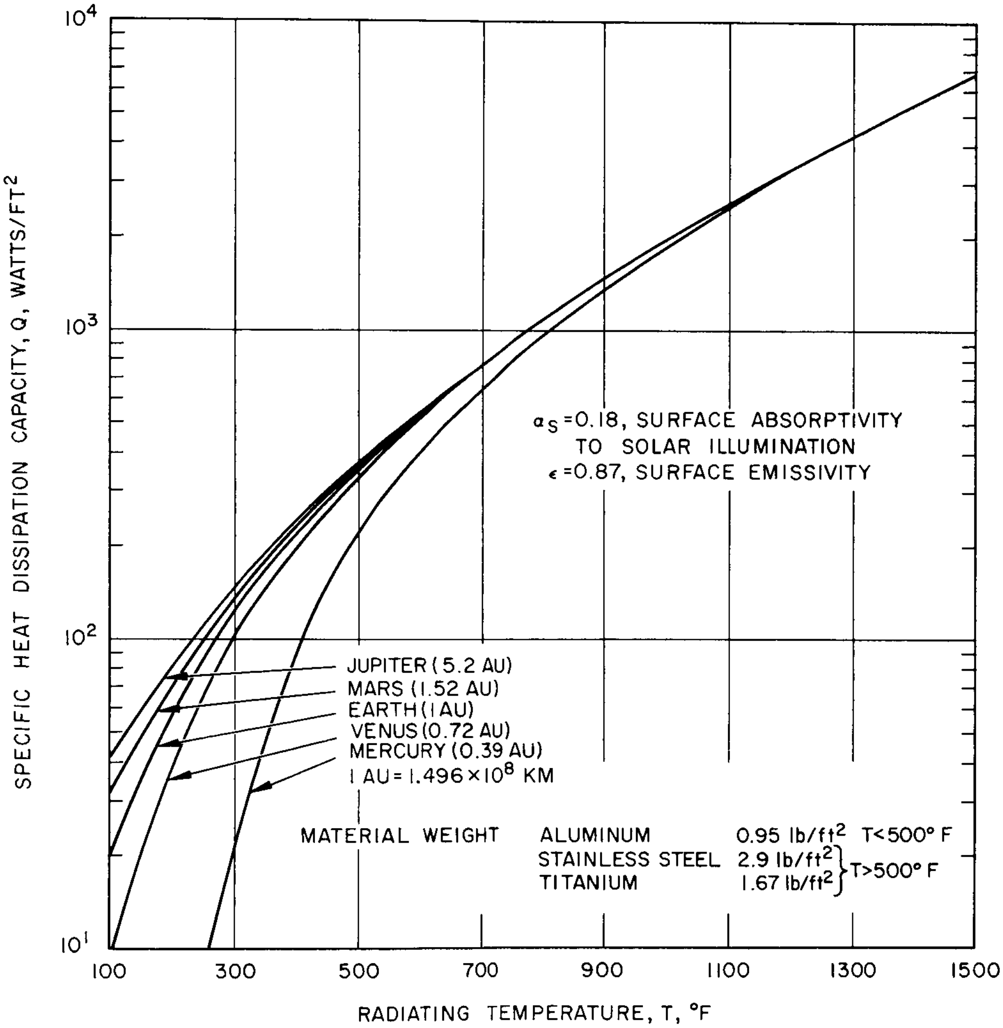


Figure 14-8. Specific heat dissipation capacity versus temperature of radiators in direct sunlight at various solar distances.

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*Typical of Hughes B6003 inorganic white paint.

14.6 NOMENCLATURE

A	radiator area
B	tube spacing
C_H	radiator cost
D	inside tube diameter
f	friction factor $= 0.079\ R_e^{-0.25}$
g	gravitational constant
H	solar illumination (watts/ft^2)
k	conductivity of fin material
K_e	transmitter efficiency
L	length along tube
M_r	radiation modulus $= B^2\ \epsilon\ \sigma\ T^3/kt$
N	number of tubes
P	pressure
ΔP_M	pressure rise due to momentum loss
Q	heat dissipation capacity (watts/ft^2)
R_e	Reynolds number
T	radiating surface temperature
T_{eff}	radiator effective temperature
T_{in}	radiator inlet temperature
T_{out}	radiator outlet temperature
ΔT	$T_{in} - T_{out}$
T_R	radiator temperature
T_s	sink temperature
T_x	temperature point on radiating fin

t	fin thickness
U_o	vapor velocity at condenser inlet
u	velocity of two-phase mixture flow in condenser
W	total heat dissipated
W_H	radiator weight
W_T	mass flow rate
X	$\sqrt{\dfrac{\left(\frac{dP}{dL}\right)_\ell}{\left(\frac{dP}{dL}\right)_g}}$
x	distance along fin from base
α_s	surface absorptivity to solar illumination
ϵ	surface emissivity
η	fin effectiveness
θ	angle between incident solar illumination and normal to the radiator surface
μ	micron
μ_g	vapor viscosity
μ_ℓ	liquid viscosity
ρ	two-phase mixture density
ρ_g	vapor density
ρ_ℓ	liquid density
σ	Stefan-Boltzmann constant
φ_g	dimensionless parameter which correlates pressure gradients for two-phase flow and single-phase flow, viz., $(dP/dL)_{TPF} = \varphi^2\,(dP/dL)_g$
$(dP/dL)_g$	pressure gradient per unit tube length for gas (vapor) phase alone

$(dP/dL)_{\ell}$	pressure gradient per unit tube length for liquid phase alone
$(dP/dL)_{TPF}$	two-phase flow frictional pressure gradient per unit tube length

14.7 REFERENCES

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